
SEISMIC EXPLORATION

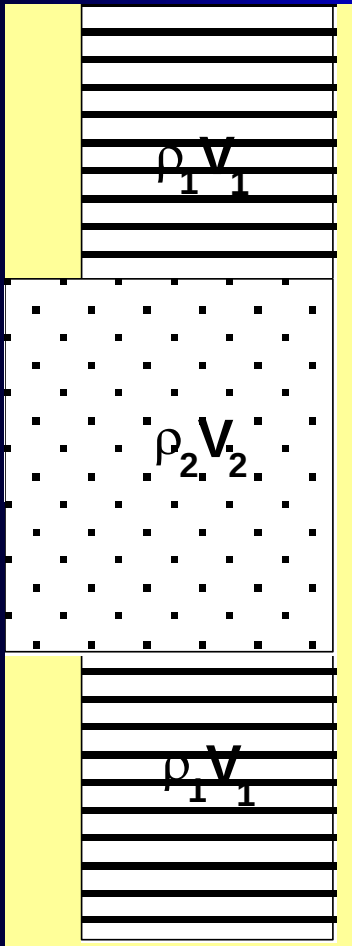
Dr. ALI BAKR

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3. **AVO Amplitude Versus Offset**
4. **Seismic Inversion**
5. **Seismic Stratigraphy**
6. **Sequence Stratigraphy**
7. **4D seismic (Time Laps)**

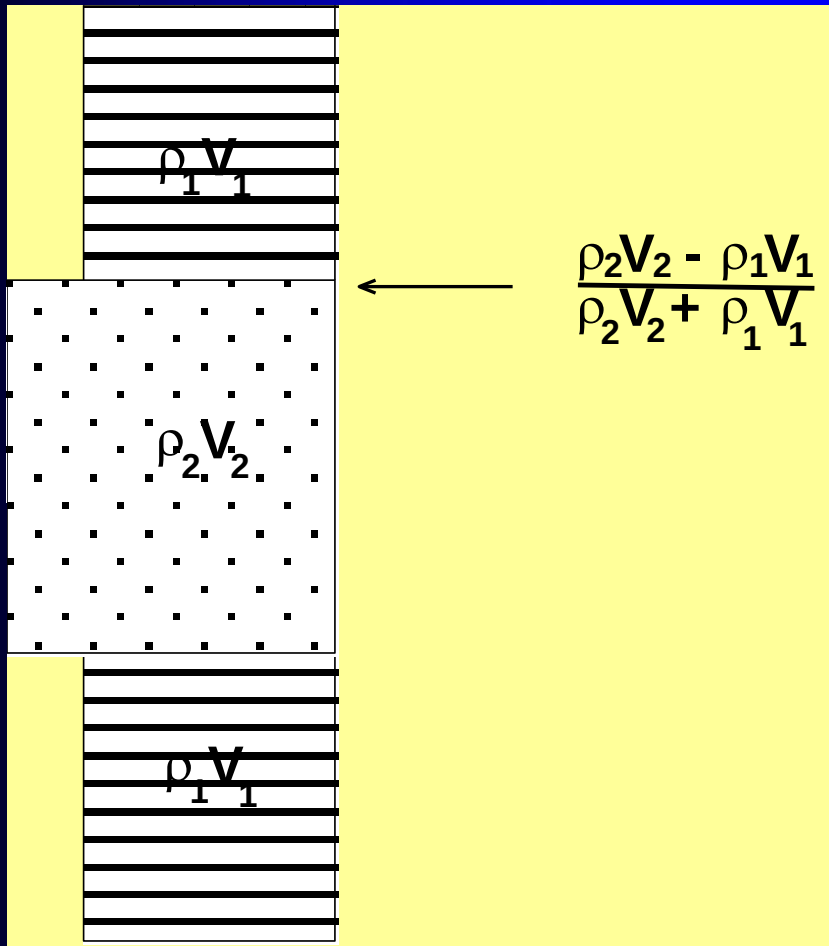
1-BASIC BACKGROUND

1-Basic Background



- Some energy will be reflected, some will be transmitted where there is a change in AI
- Amount reflected (amplitude of reflection) will depend on the relative difference in physical properties across the interface

1-Basic Background



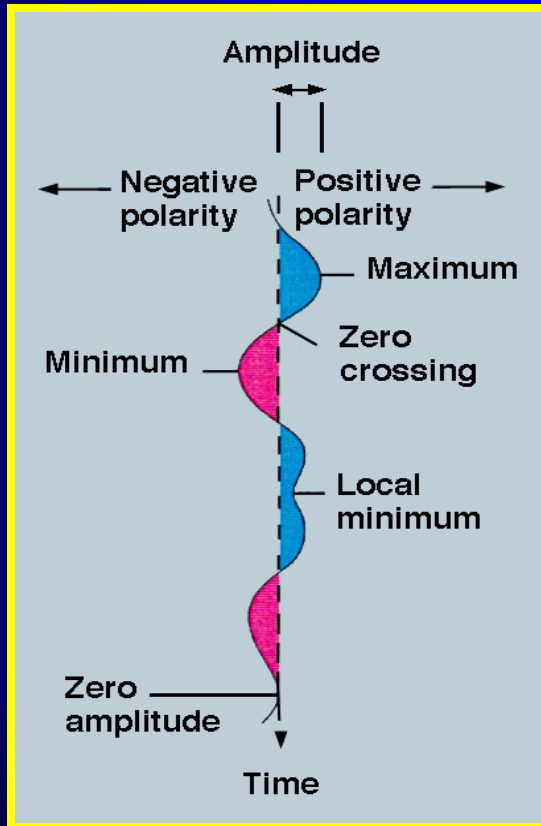
- Define reflection coefficient (RC)

$$RC = \frac{AI_2 - AI_1}{AI_2 + AI_1}$$

- If $AI_2 > AI_1$ – positive RC
- If $AI_2 < AI_1$ – negative RC

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Polarity Conventions

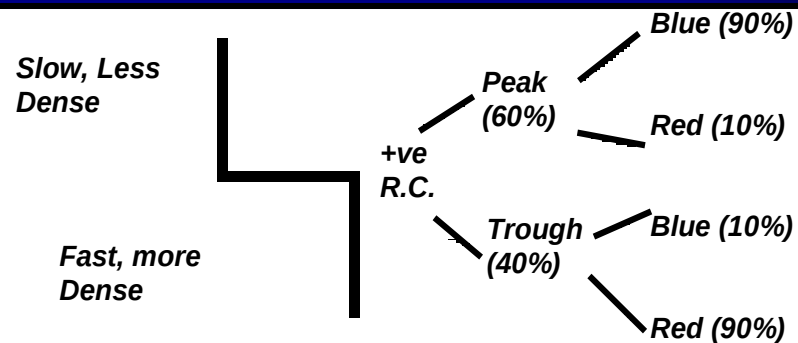


Normal Polarity: Trough = negative reflection coefficient = impedance decrease

Reverse Polarity: Peak = negative reflection coefficient = impedance decrease

SEG Standard: Trough = compression = positive reflection coefficient = impedance increase

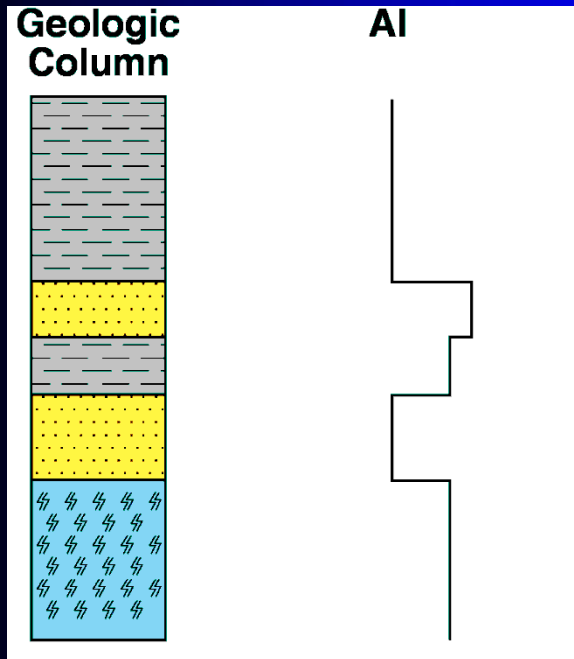
North Sea Standard = SEG Standard



1-*Basic Background*

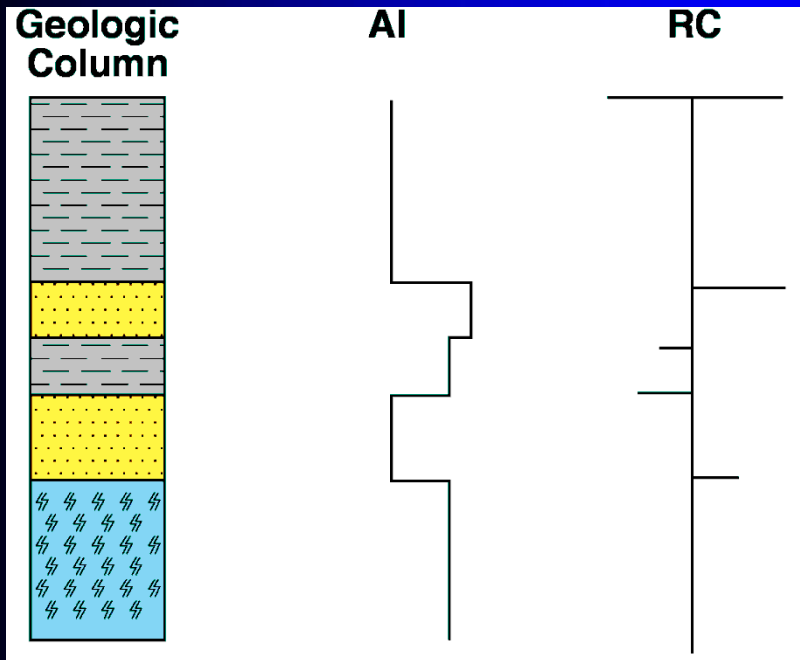
- Not all changes in lithology associated with change in AI. Changes in fluid content in a single lithology can give rise to reflections
- Different combinations of layers lithologies can have the same RC Seismic “non-unique”
- Seismic data image *interfaces* – we observe changes in AI across an interface, not properties of layers themselves

1-*Basic Background* *Convolutional Theorem*



Subsurface at any one location as consists of a one-dimensional series of reflection coefficients

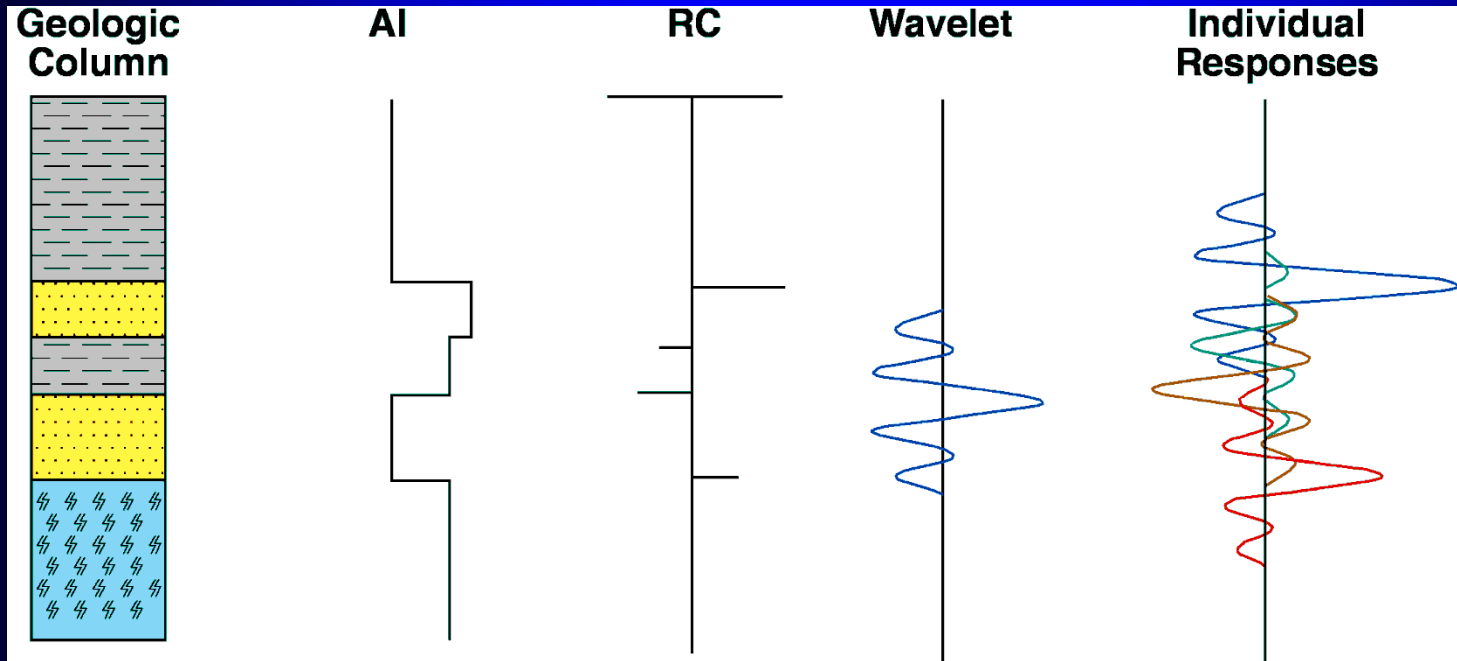
1-*Basic Background* *Convolutional Theorem*



Subsurface at any one location as consists of a one-dimensional series of reflection coefficients

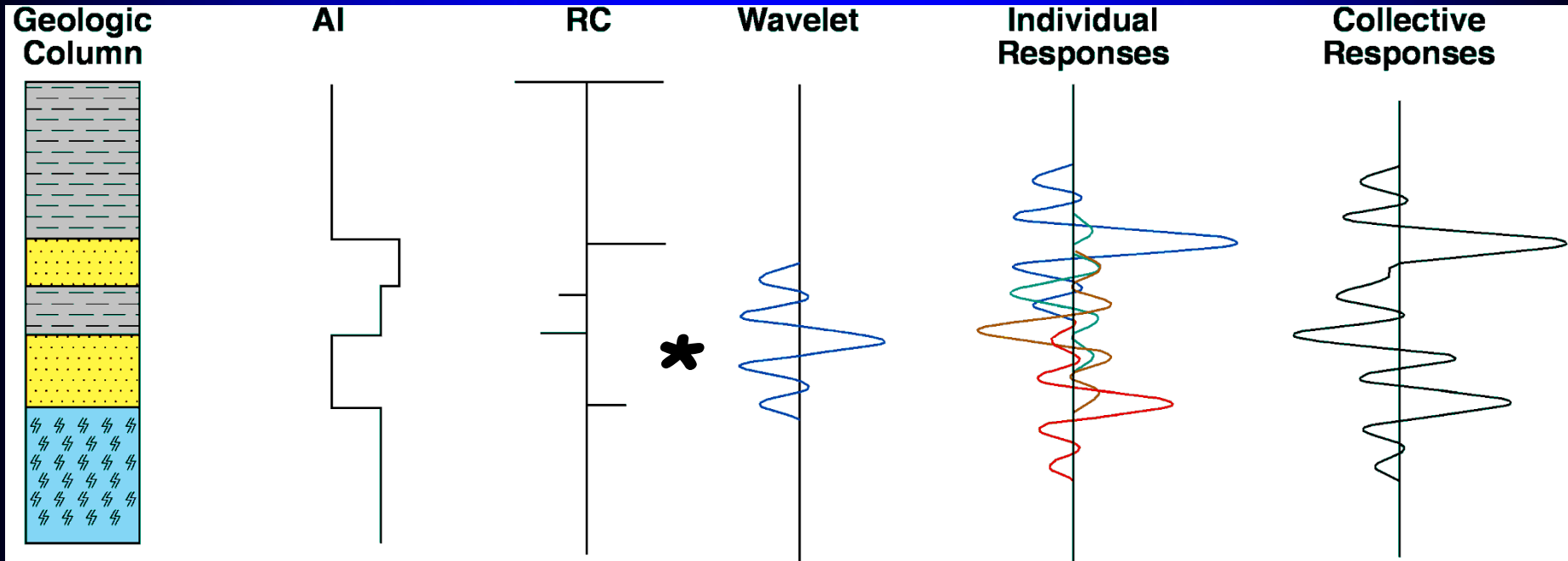
1-Basic Background

Convolutional Theorem



Each RC gives rise to a separate reflection event, the amplitude of which is proportional to the change in AI across the interface

1-Basic Background Convolutional Theorem



- The final image we will record for that location consists of the algebraic sum of all the individual reflections
- Mathematically we “convolve” the wavelet with the series of reflection coefficients

1- Basic Background

Data required for synthetic calculation

- Seismic Data
- Well Curves (Sonic and Density)
- Well Position relative to Seismic
- Check Shot / T-D relationship
- Well Deviation Survey
- Seismic Acquisition and Processing Info

1- Basic Background

Wavelet Estimation Work Flow

- Load Seismic Data
- Validate / Adjust X-Y Coordinates
- Load Well Curves
- Load Well Tops and Horizons
- Create Synthetic & Check Well Tie
- Adjust Well Tie if Necessary
- Estimate Wavelet
- Check Quality and Stability of Estimated Wavelet

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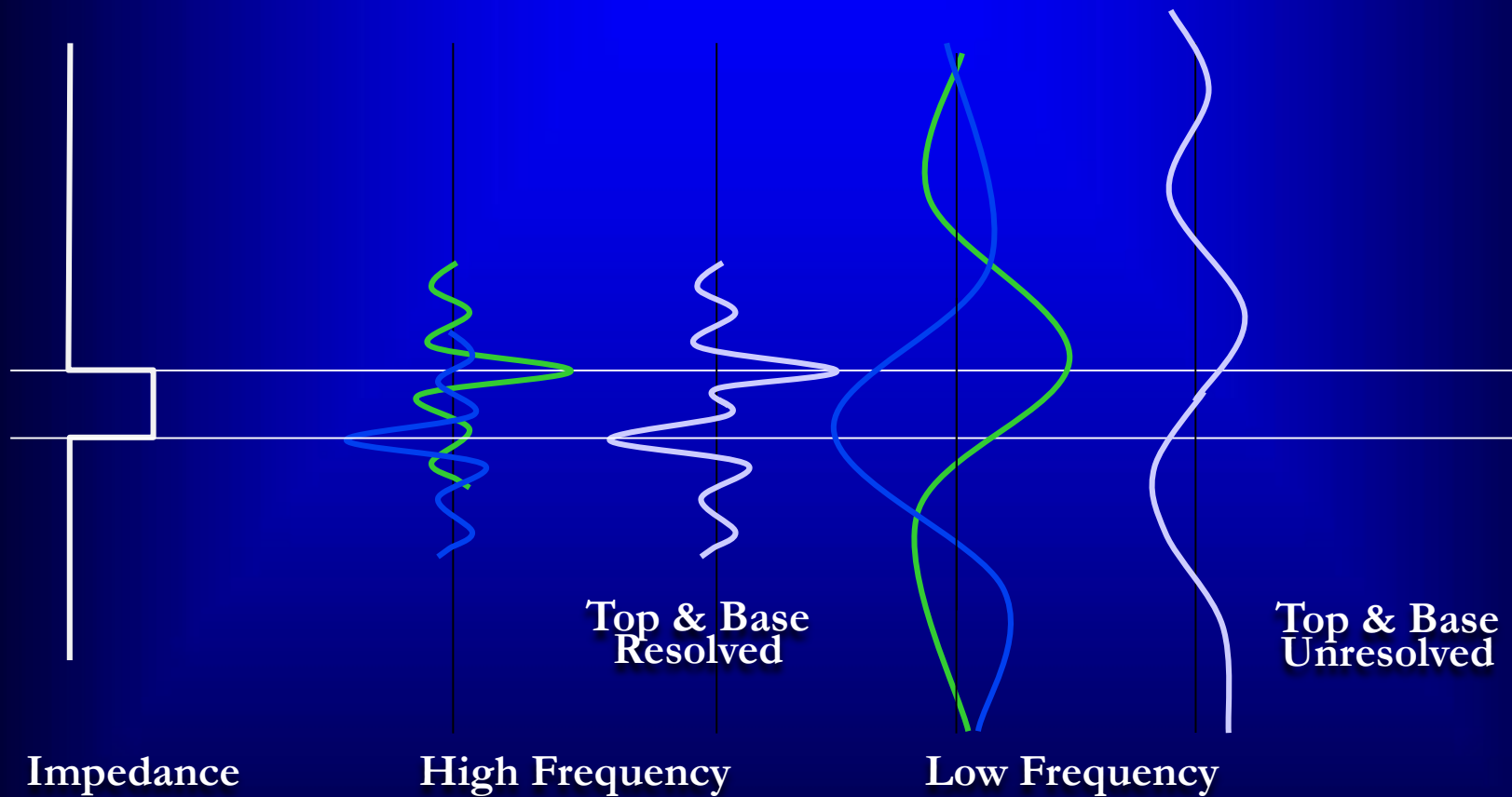
Seismic Resolution

What do we mean by Resolution?

- Bandwidth?
- Detect-ability?
- Discrimination?
- Measurability?
- Model parameters?
- ...?

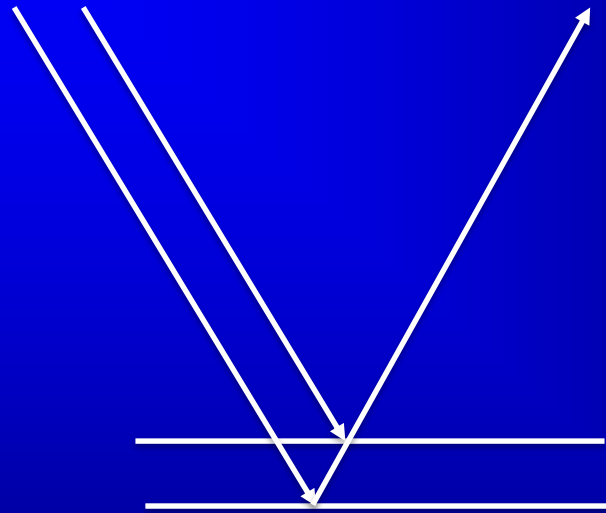
1-Basic Background

Vertical Resolution



1-Basic Background

Vertical Resolution



Seismic ability to define top
and bottom of a rock layer

In general, reflections are composites of thin layer effects.

1-Basic Background

Vertical Resolution

Resolution depends on:

Frequency content in seismic data.

The interval velocity at the objective level

Dominant Wavelength of Seismic Wave =

$$\lambda = \frac{V}{f}$$

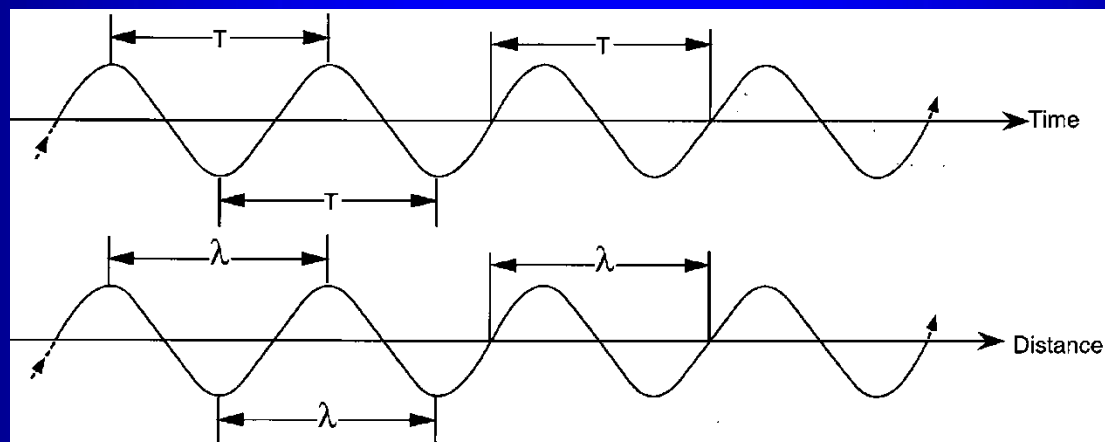
Where: V is the velocity in unit distance per second and

f is the dominant frequency in Hz

$$R_v \cong \frac{V_{\text{int}}}{4f_{\text{dom}}}$$

1-Basic Background

Vertical Resolution



<u>Parameter</u>	<u>Symbol</u>	<u>Units of Measurement</u>
Period	T	seconds (s)
Frequency	f	Hertz (Hz = cycles/sec)
Wavelength	λ	meters (m) or feet (ft)
Wave Number	k	cycles/m (c/m) or cycles/ft (c/ft)
Velocity	V	m/s or ft/s

$$f = 1/T$$

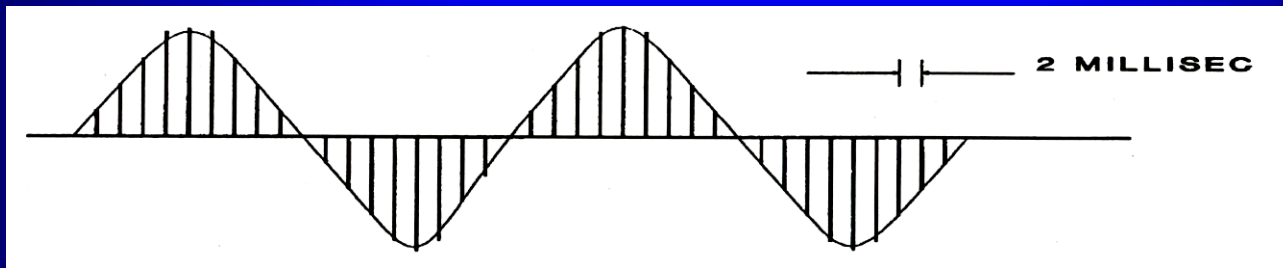
$$k = 1/\lambda$$

$$V = f\lambda$$

1-Basic Background

Vertical Resolution

Exercise



Given the above wavelet,

1. What is the frequency of the wavelet?
2. What is the wavelength in a layer of velocity 3800 m/sec?

1-Basic Background

Vertical Resolution

- Most of the energy in a seismic wavelet is contained in a band of frequencies centered about the dominant frequency. The dominant period can be defined as the time between two major crests. The dominant frequency is the reciprocal of the dominant period. The equation for wavelength, λ , is:

$$\lambda = \text{velocity} / \text{frequency}$$

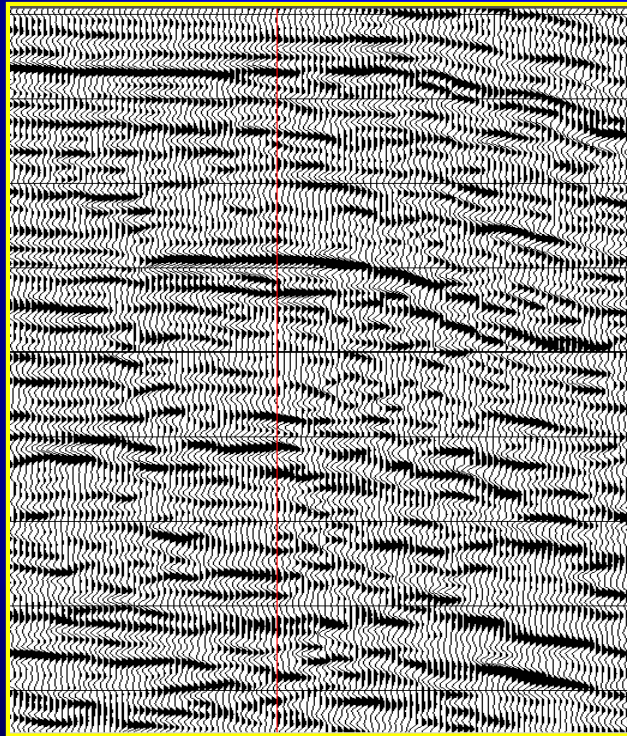
Calculate wavelengths for the following cases:

Shallow rocks: $V=2000 \text{ m/s}$, $f=50 \text{ Hz}$;

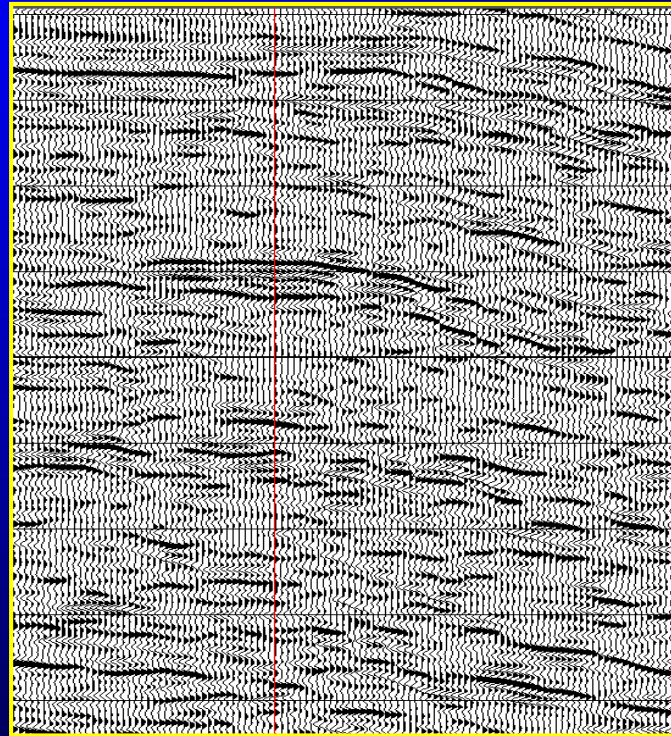
Deep rocks: $V=6000 \text{ m/s}$, $f=25 \text{ Hz}$.

1-Basic Background Vertical Resolution

Conventional



HFI™



Vertical Resolution – Example ('HFI' Processing from Geotrace)

1-Basic Background

Vertical Resolution

- Example 1:

$$V = 7,000 \text{ m/s}$$

$$F = 50 \text{ Hz}$$

$$\lambda = \frac{V}{f} = 7,000/50 \text{ [(m/s)/(cycles/s)]} = 140 \text{ m}$$

1-Basic Background

Vertical Resolution

- Example 2:

$$V = 3,000 \text{ m/s}$$

$$F = 50 \text{ Hz}$$

$$l = V/F$$

$$= 3,000/50 \text{ [(m/s)/(cycles/s)]}$$

$$= 60 \text{ m}$$

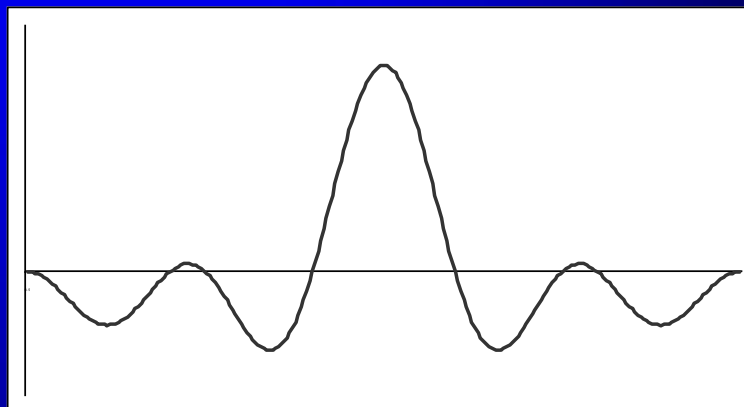
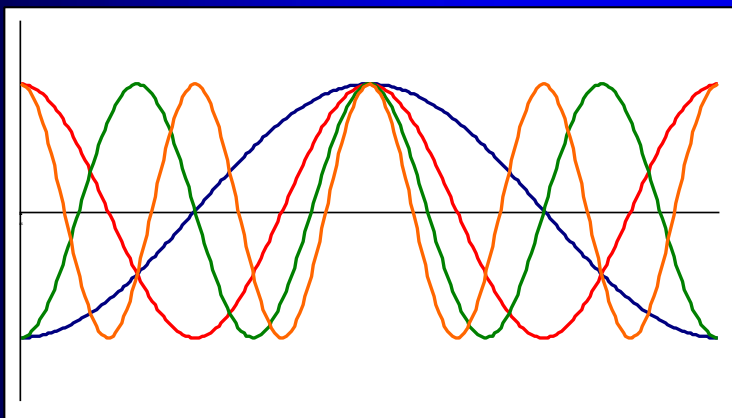
1-Basic Background

Vertical Resolution (Summery)

- Vertical Resolution is the ability to detect and map thin events such as reservoir sand bodies
- It is determined by the average frequency and bandwidth of the seismic data
- We can typically resolve down to $\frac{1}{4}$ wavelength
- Wavelength is determined by frequency and velocity:
$$\lambda = V/f \text{ so resolution } \sim V/(4*f)$$
- Resolution deteriorates with depth

1-Basic Background

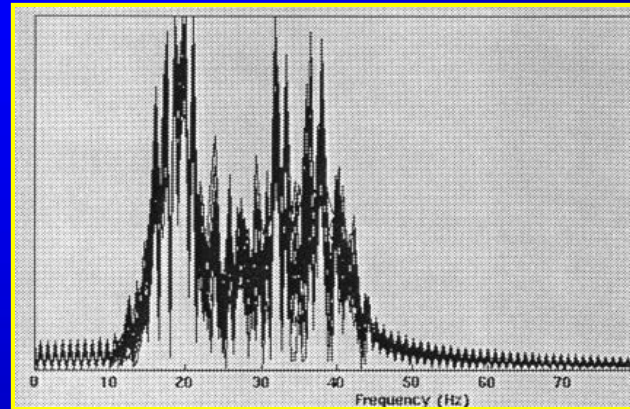
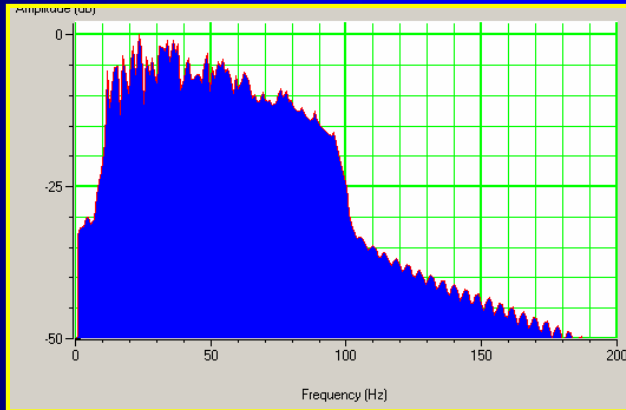
Vertical Resolution



- The seismic signal contains a range of frequencies (left)
- The broader the bandwidth, the sharper the pulse (smaller side lobes)

1-Basic Background

Vertical Resolution

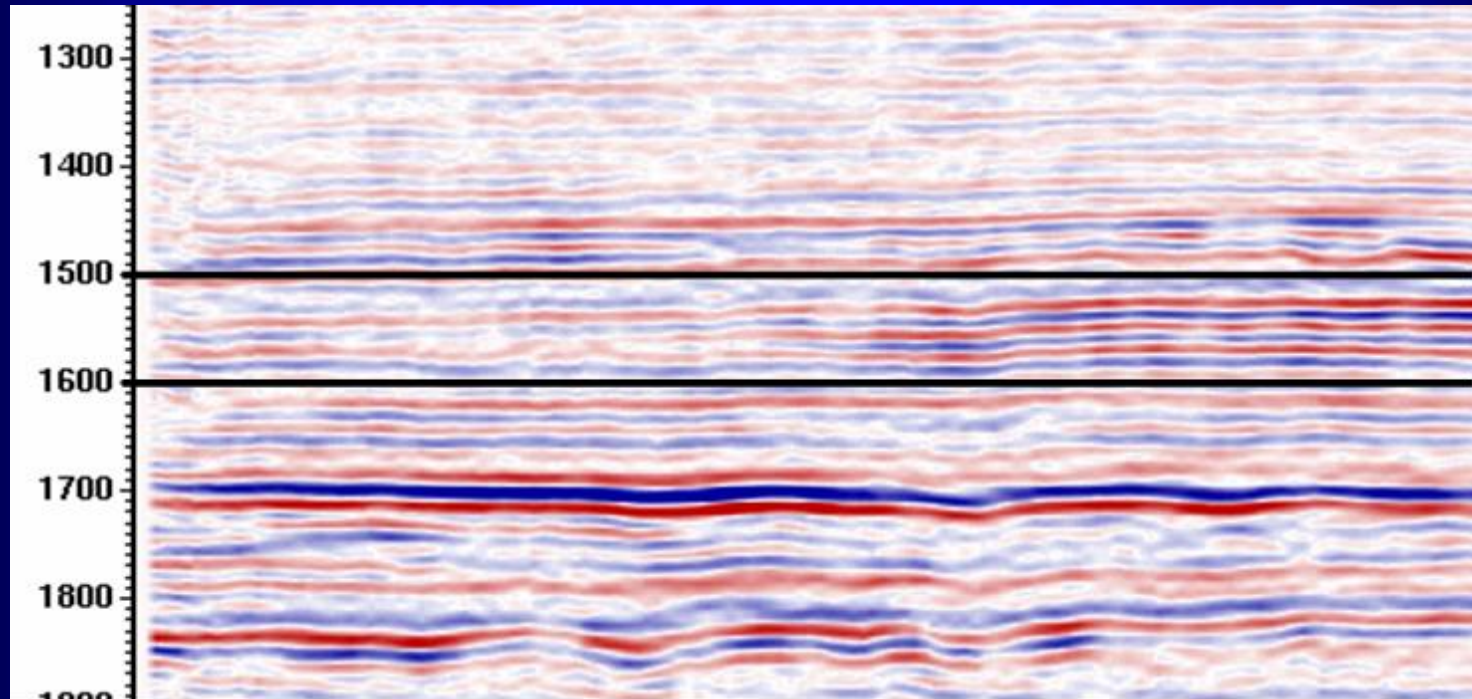


Fourier analysis may be used to see the bandwidth of the seismic data in a given portion of the data.

- Amplitude spectrum on left shows a broad bandwidth, rich in high frequencies
- Spectrum on right is irregular and abruptly truncated at about 45 Hz. Data were filtered post-stack as a noise reduction exercise.

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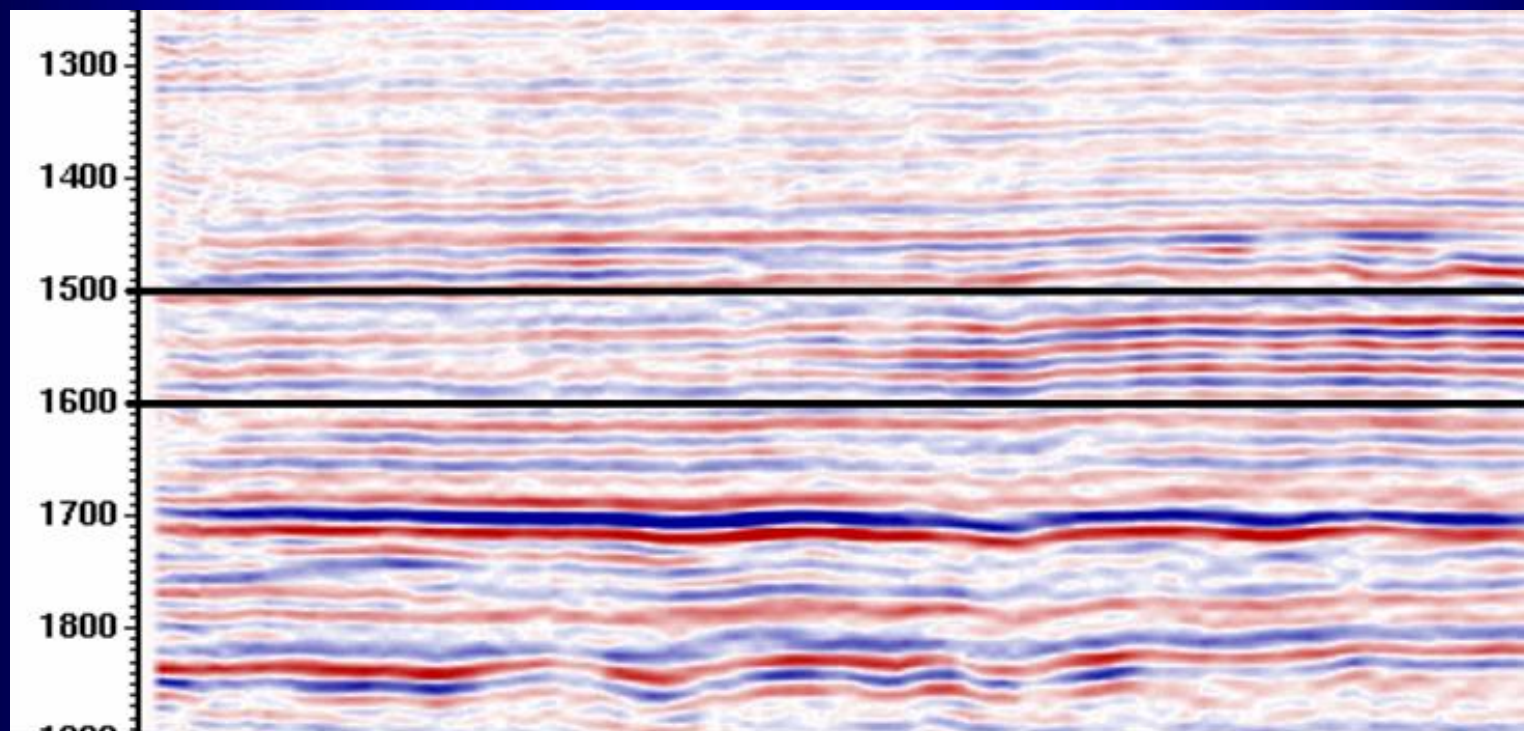
Vertical Resolution



What is the dominant frequency of the seismic data in the interval between 1500 and 1600 ms? If the velocity is 5000 m/s, what is the tuning thickness? If it is possible to detect a bed down to 1/16 of the wavelength, what would that be?

1-Basic Background

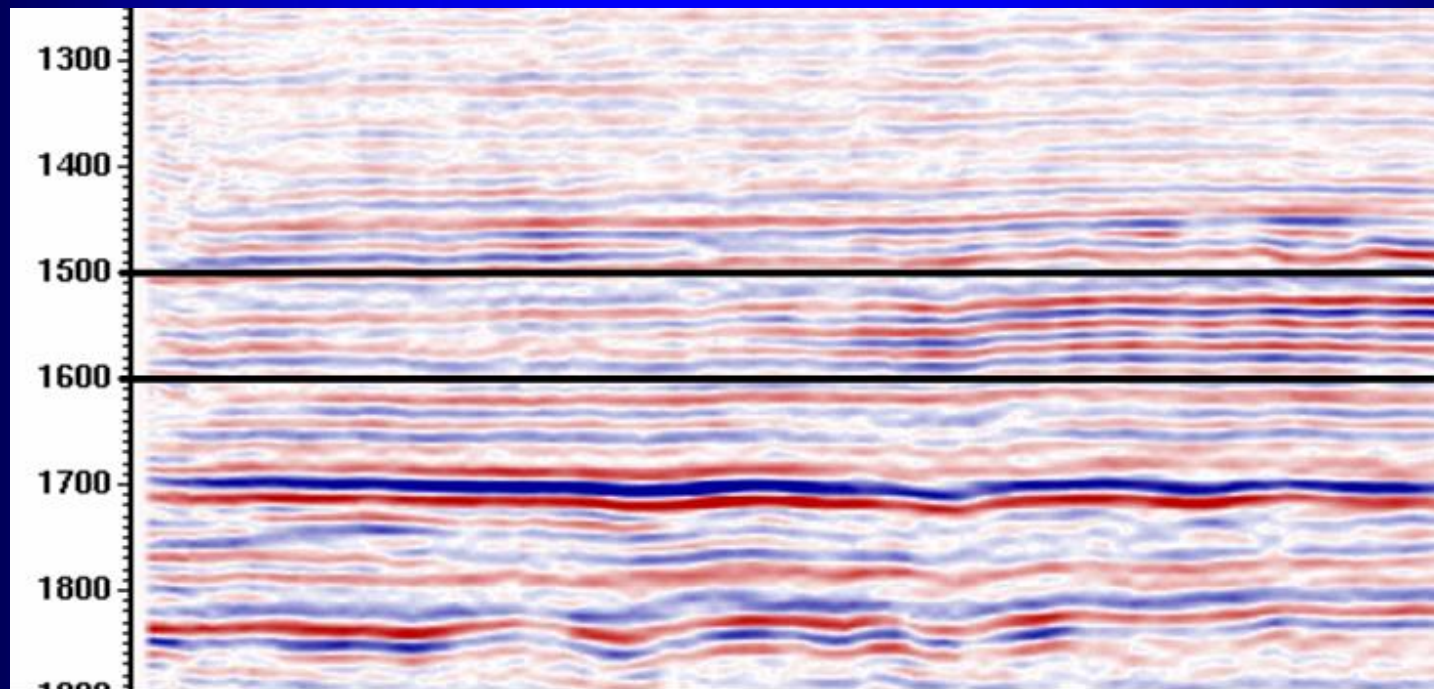
Vertical Resolution



Dominant frequency:
about $4 \frac{1}{2}$ cycles in 100 ms
= 45 cycles/second = 45 Hz

1-Basic Background

Vertical Resolution



Tuning thickness:

Frequency = 45 Hz, Velocity = 5000 m/s

Wavelength = $5000/45 = 111$ m

Tuning thickness = $\frac{1}{4} \times 111 = 28$ m

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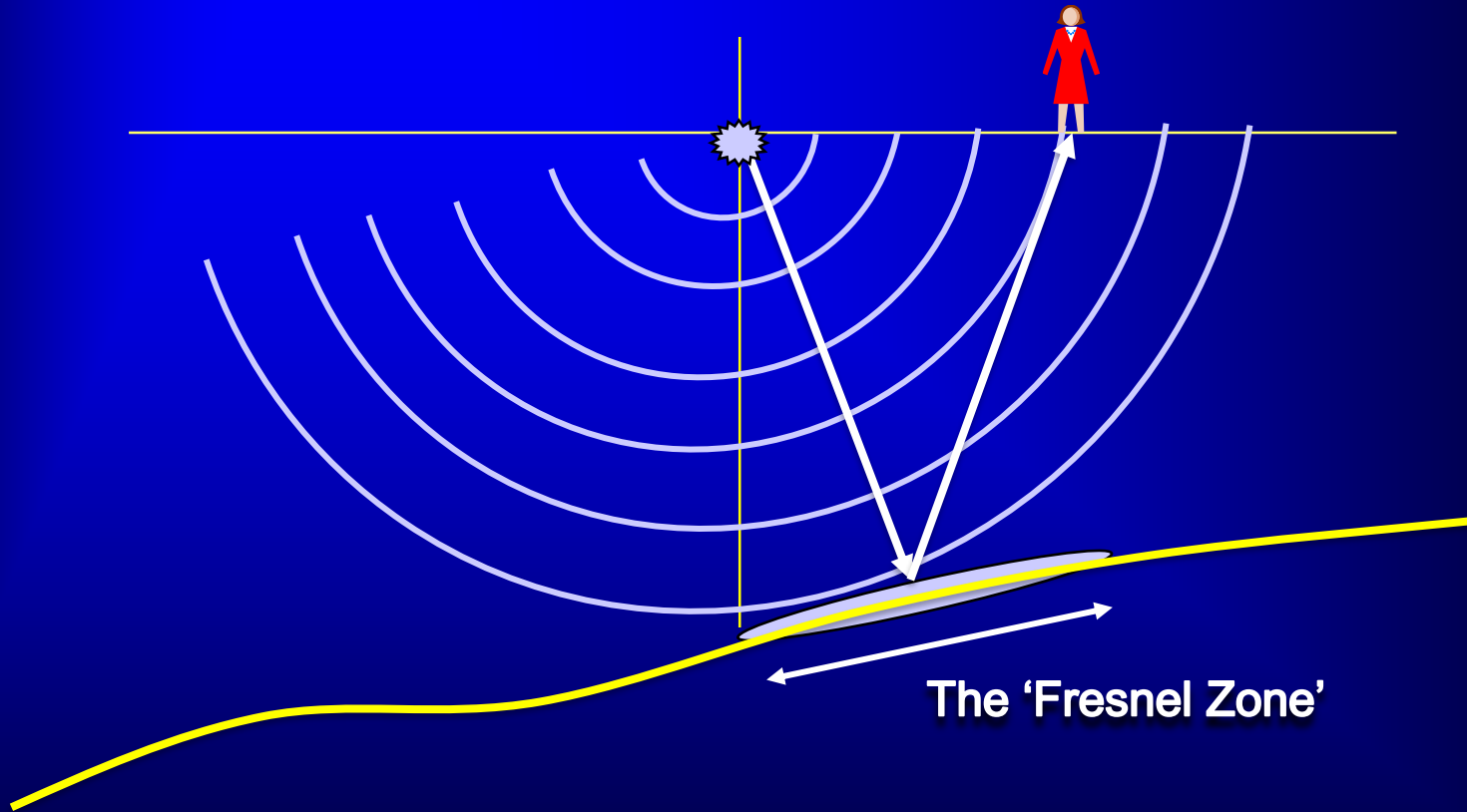
Horizontal Resolution

- Horizontal Resolution is the ability to map lateral changes in reservoir – edges and internal structures.
- Seismic energy is reflected from a patch rather than a point. Migration collapses this patch and improves resolution.
- Prior to migration horizontal resolution is poor
- Horizontal resolution can approach vertical resolution if 'aperture' is adequate
- The wider the aperture the closer the horizontal resolution approaches the vertical resolution
- Other seismic processes can also reduce lateral resolution

1-Basic Background

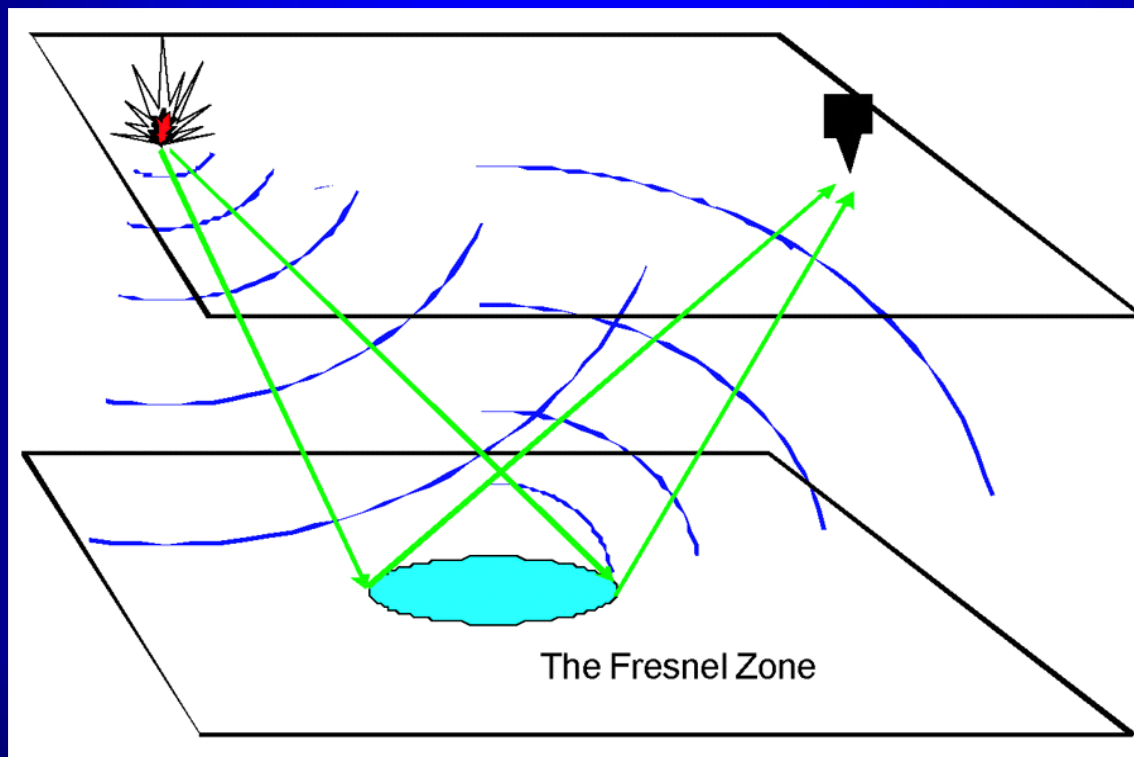
Horizontal Resolution Fresnel Zone

Seismic Energy Reflects from a Patch, not a Point



1-Basic Background

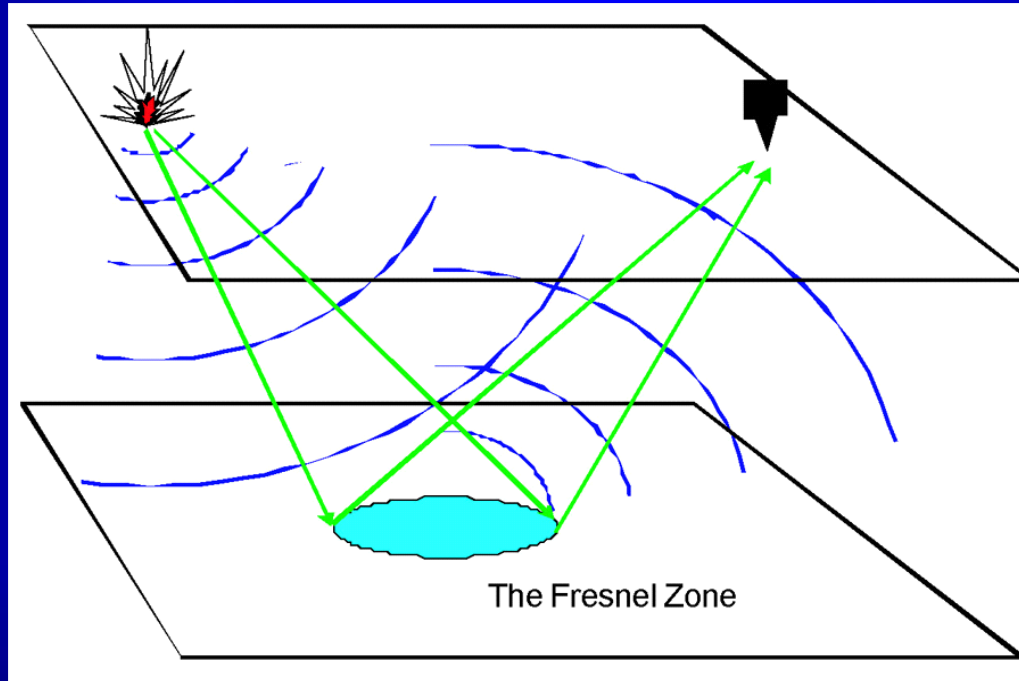
Horizontal Resolution



Lateral resolution described by Fresnel Zone
Seismic data image ("illuminate") an area, rather than a single point

1-Basic Background

Horizontal Resolution



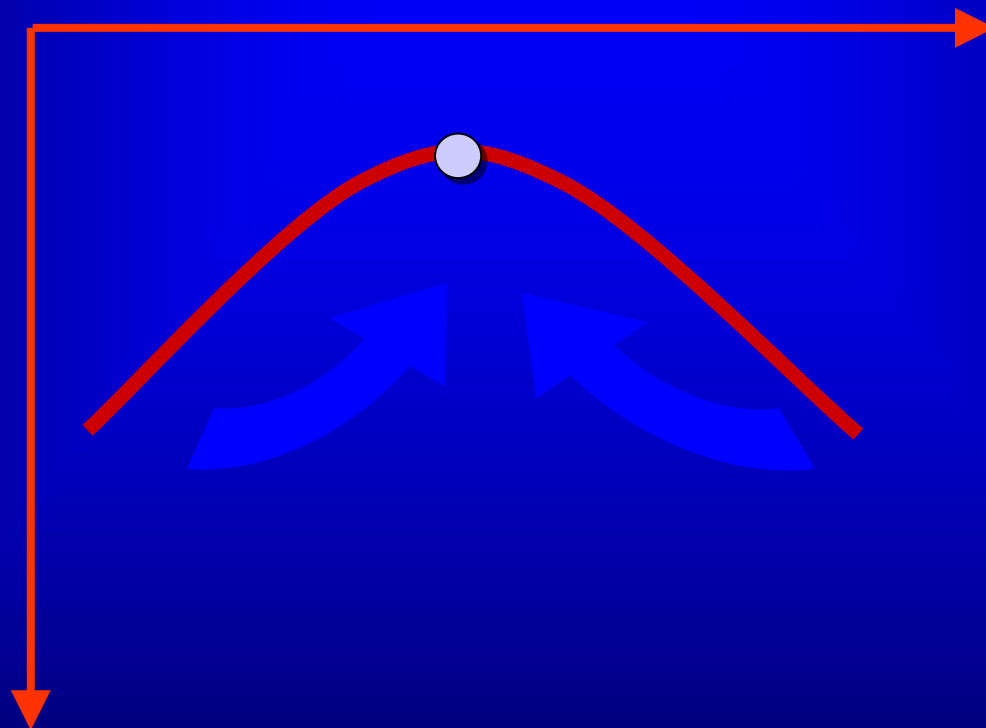
Fresnel zone diameter (F) depends upon:

- Average velocity (v)
- Two-way travel time (t)
- Dominant frequency (f)

$$F = v (t/f)^{1/2}$$

1-Basic Background

Horizontal Resolution



Migration collapses diffractions and gives us horizontal resolution

To do this properly we need to record the whole diffraction

1-Basic Background

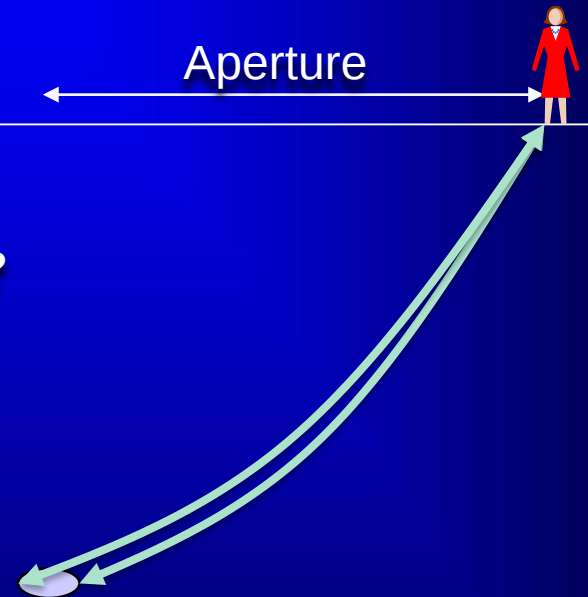
Aperture and Horizontal Resolution

Aperture – How far away can we observe from?

or – What angles do we allow into our recording/processing system?

We need large apertures to record the whole diffraction pattern so we can collapse it

Aperture needs to be greater for greater target depths



1-Basic Background

Horizontal Resolution

- Fresnel Zone example:

$$v = 2440 \text{ m/s}$$

$$f = 25 \text{ Hz}$$

$$t = 2 \text{ s}$$

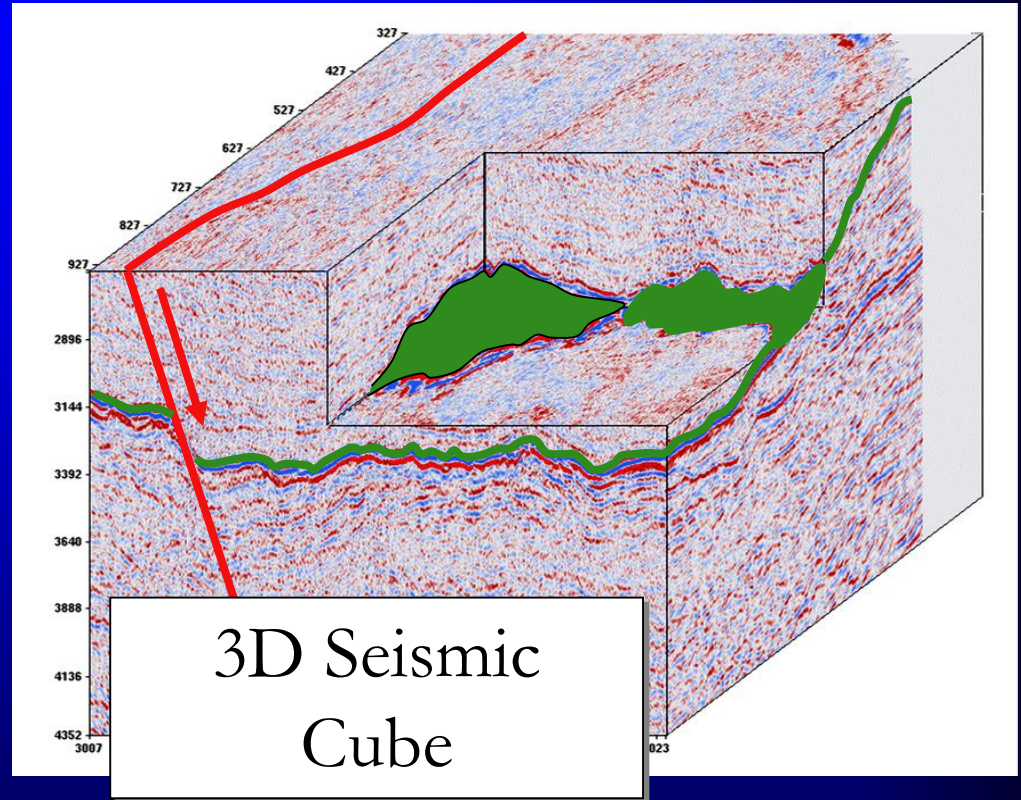
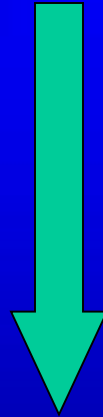
$$\begin{aligned} F &= v (t/f)^{1/2} \\ &= 2440 * (1/25)^{1/2} \\ &= 488 \text{ m} \end{aligned}$$

2- SEISMIC ATTRIBUTES

Seismic Interpretation

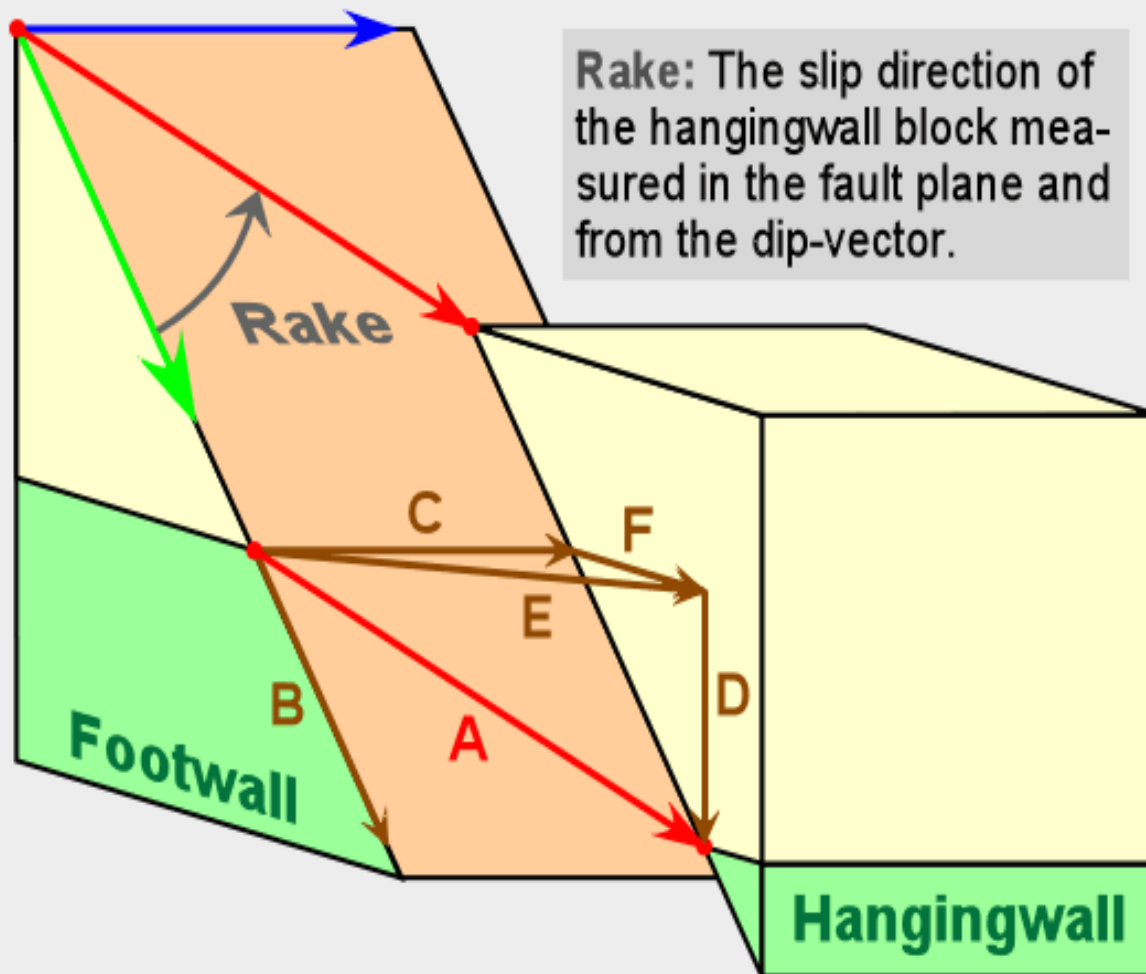
To Interpret:

Structure
Stratigraphy
Lithology
Fractures
Pressure
Pore Fluid



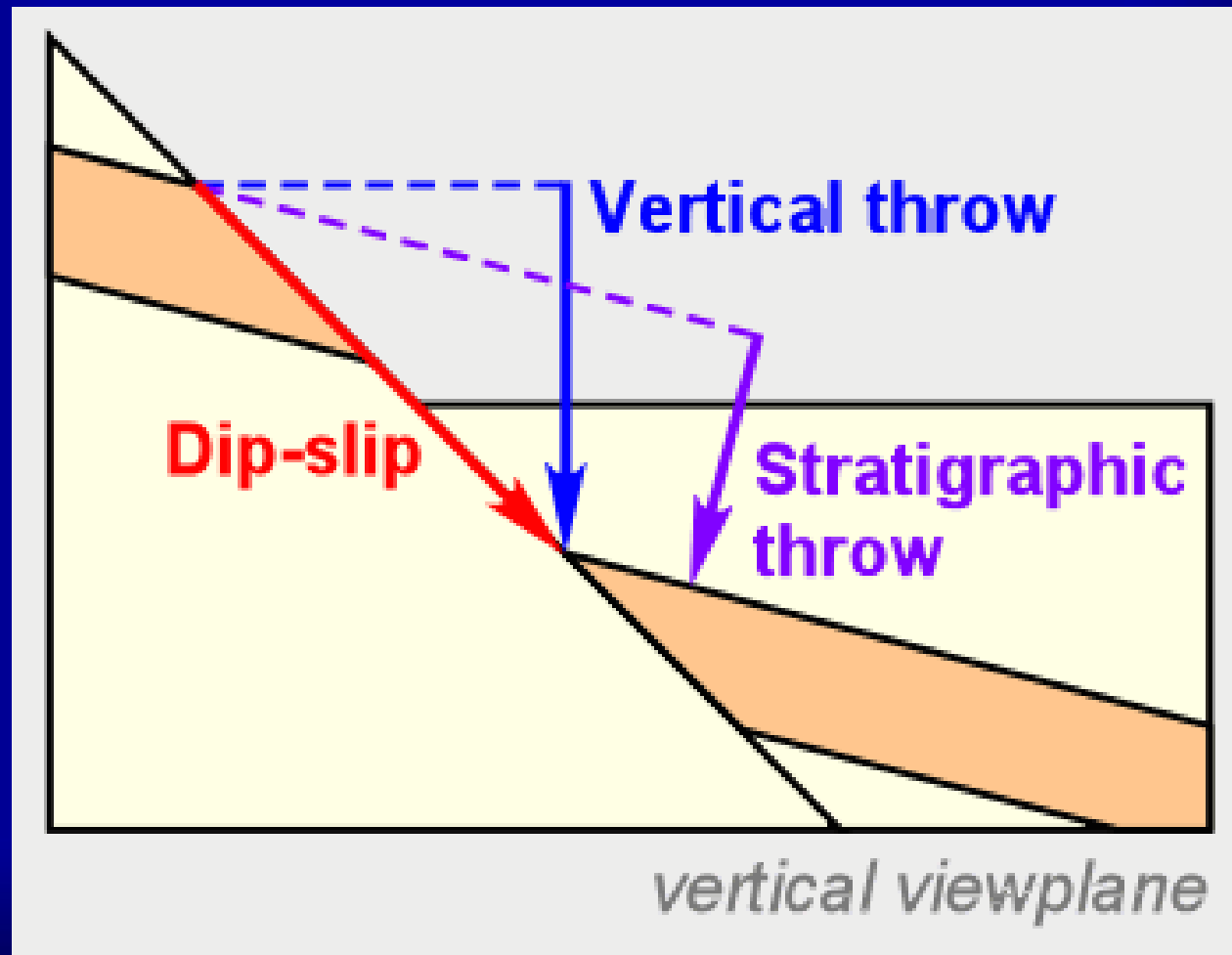
Predict and Characterize Subsurface Reservoirs

Structural Styles & Structural Interpretation



Slip amount

- A. Net-slip:** The total slip on the fault.
- B. Dip-slip:** The dip-parallel slip component.
- C. Strike-slip:** The strike-parallel slip component.
- D. Vertical throw:** The vertical component of the net-slip.
- E. Horizontal throw:** The total horizontal component of the net slip.
- F. Heave, Stratigraphic heave:** The apparent horizontal component of the net-slip.



TYPES OF NORMAL FAULTS

PLANARS

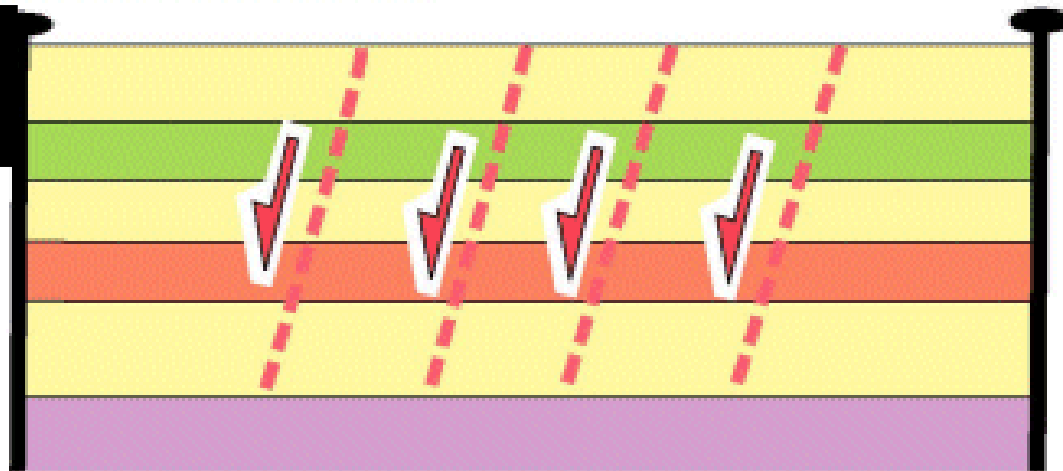
LISTRIC

GROWTH

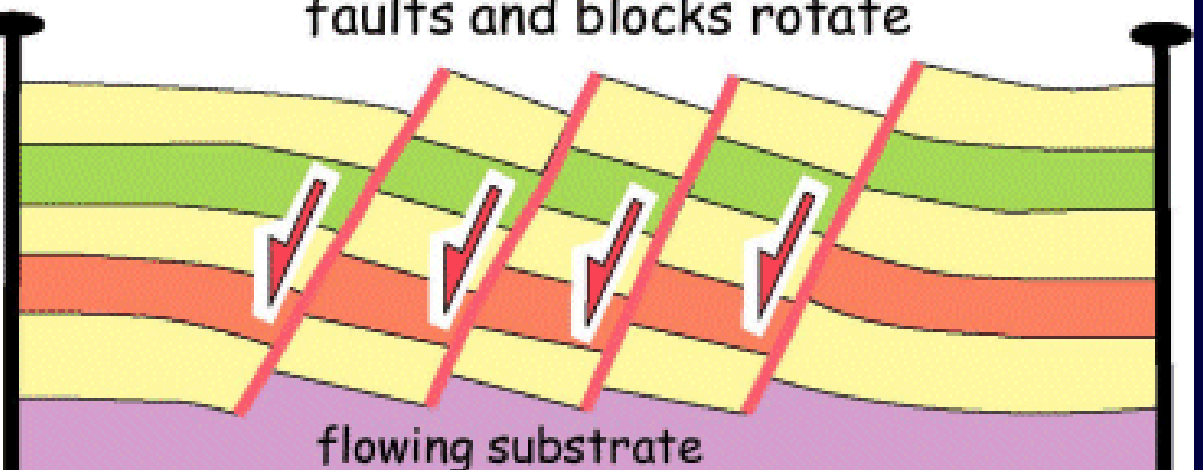
REJUVINATED

Planar Normal Faults

Domino
blocks



faults and blocks rotate



flowing substrate

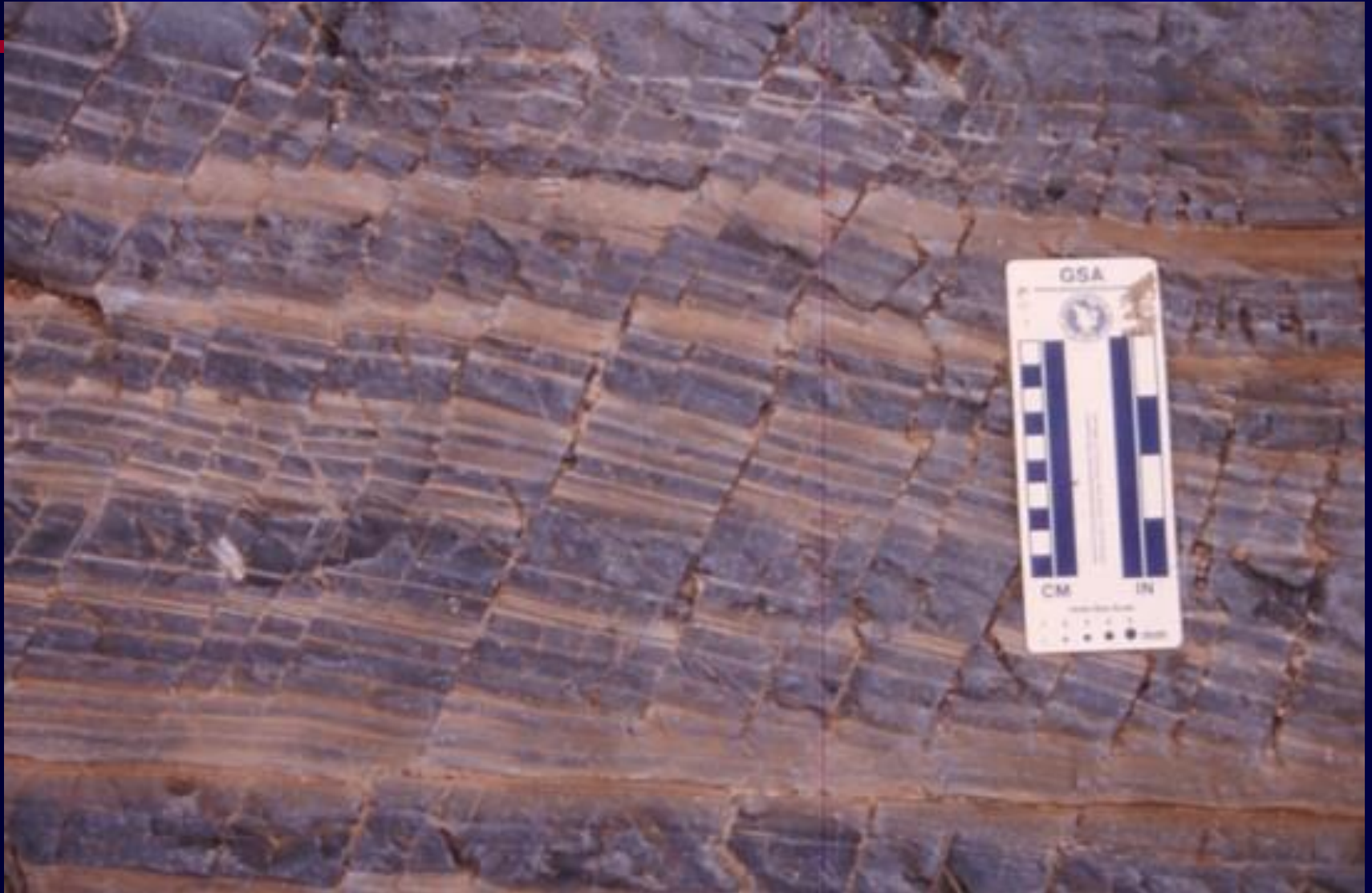
Planners normal faults



ALI BAK...

Dip angle constant with depth
Non-rotational faults

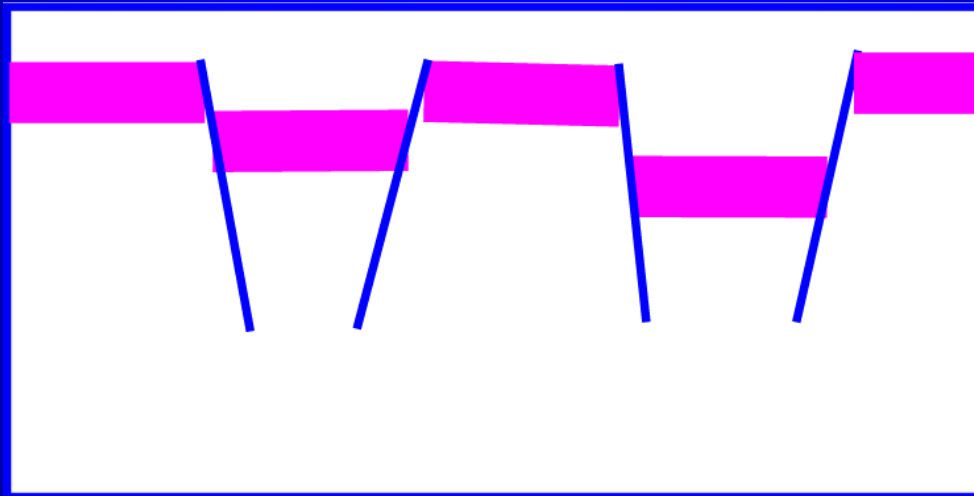
Planners Norma Faults



Planar Faults- Dip angle constant with depth Non-rotational faults



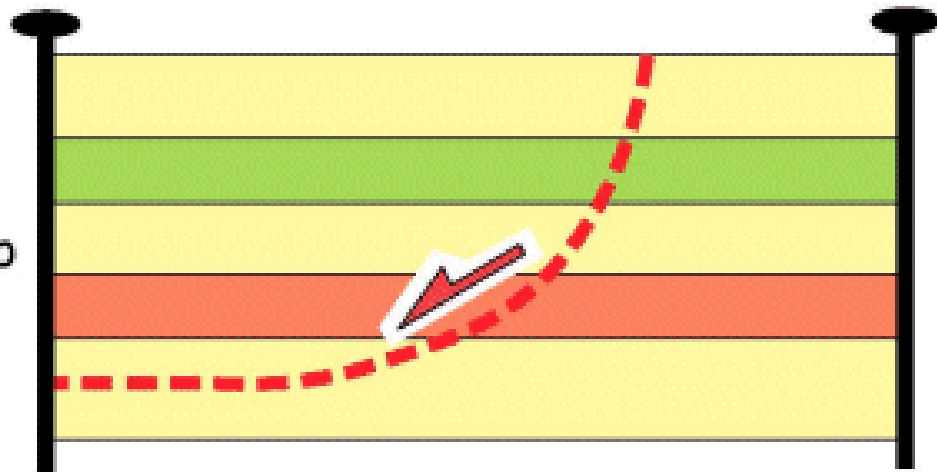
Structural Geometry of Extensional Terrains
Horst and Graben Structures-
planar fault geometry
Faults “die out” with depth



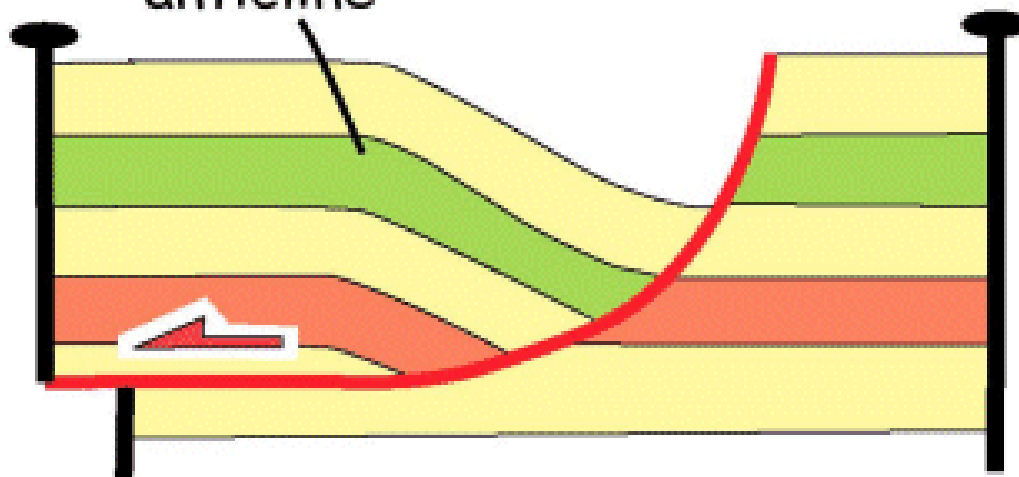
Listric Normal Fault

listric =
"spoon-shaped"

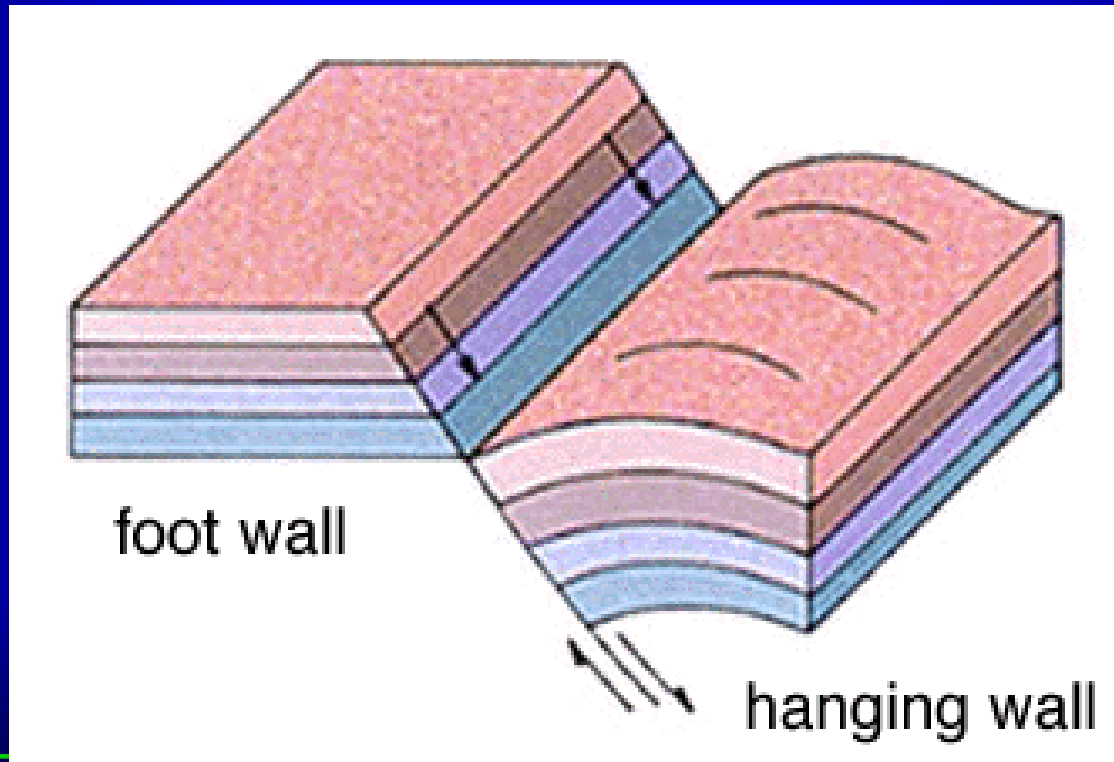
fault reduces in dip
as it goes deeper



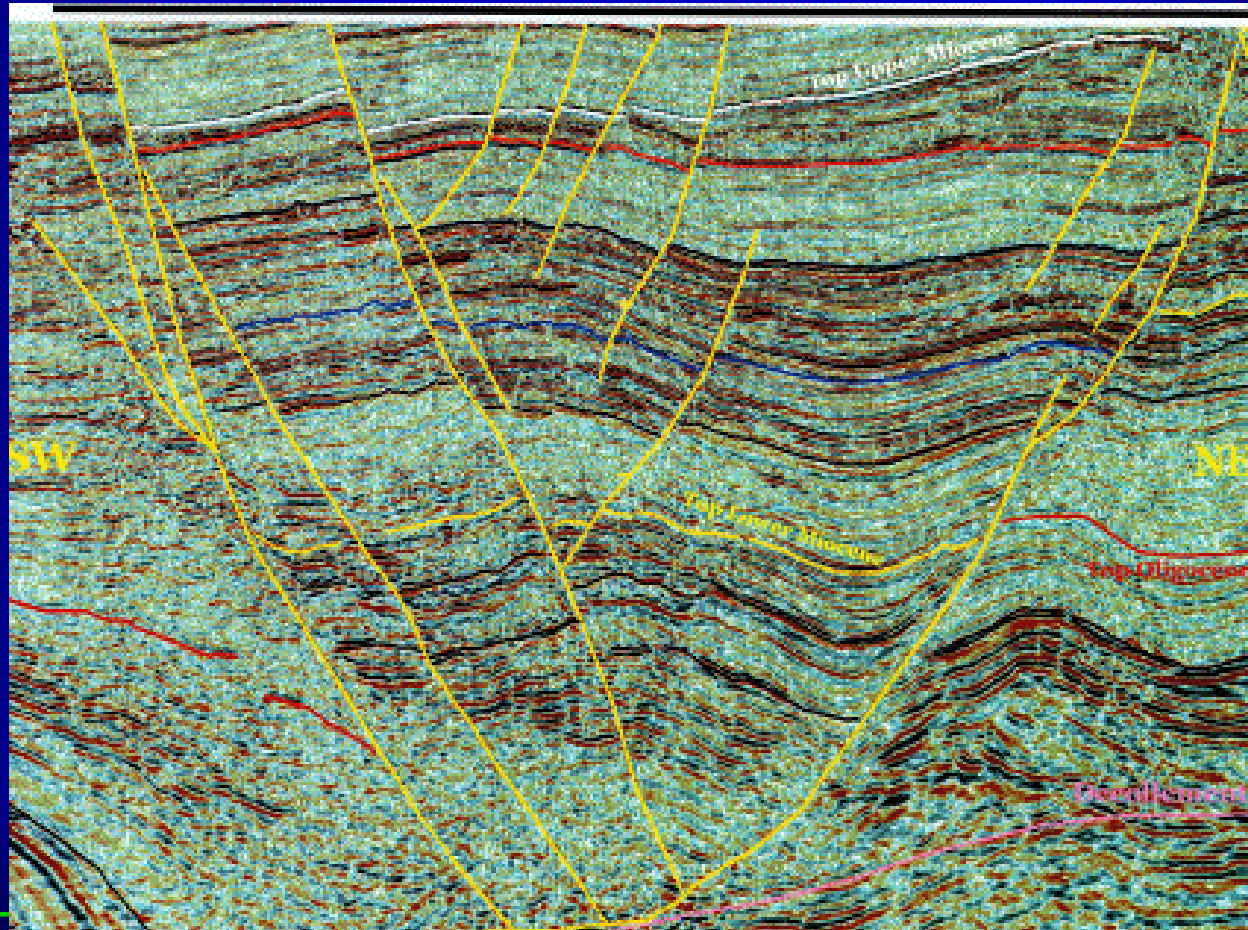
"roll-over"
anticline



Growth fault. Growth faults are a particular type of normal fault that develops during ongoing sedimentation, so the strata on the hanging wall side of the fault tend to be thicker than those on the footwall side.



Fault Growth

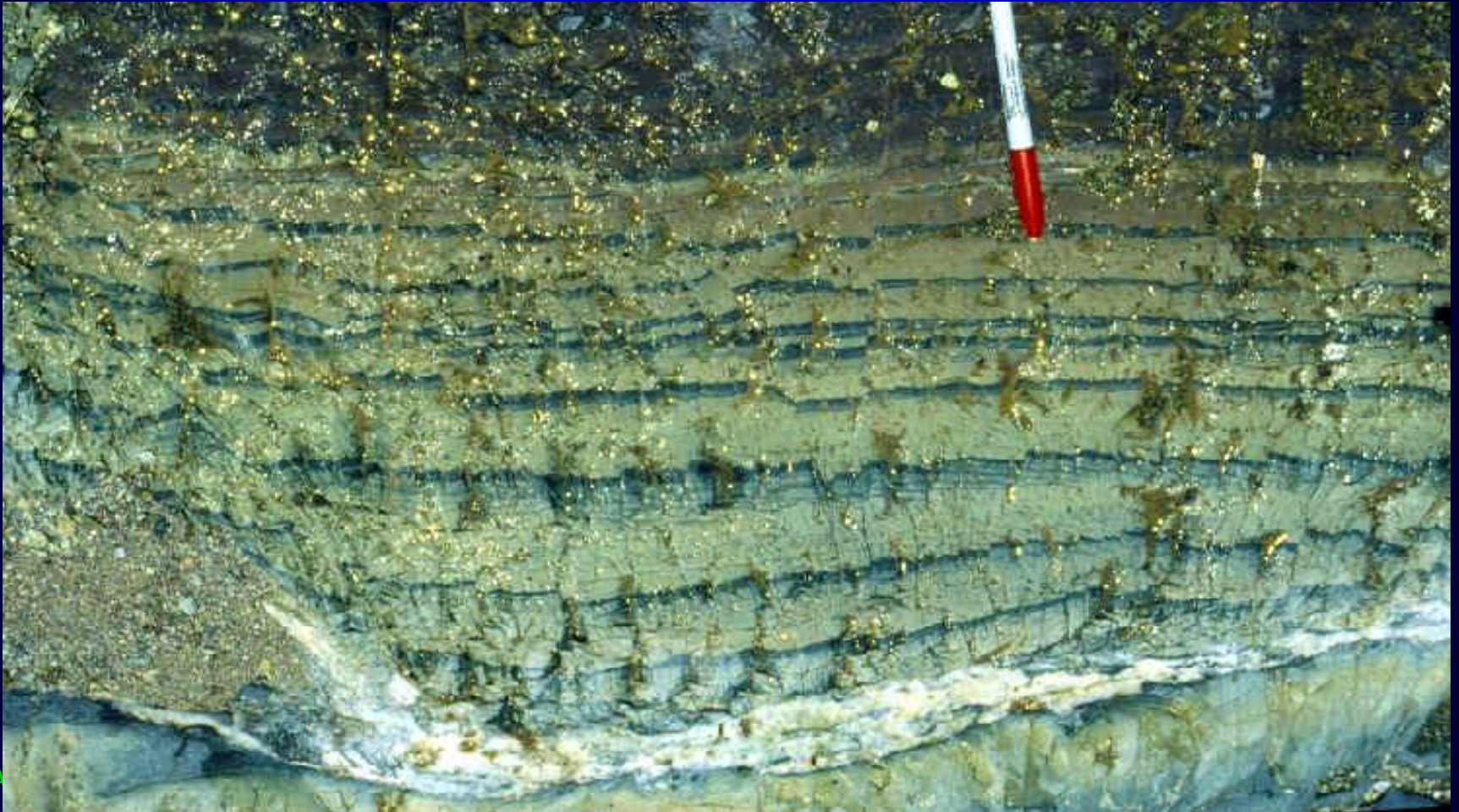


Fault Growth



Listric Faults

Curved faults, Dips decrease with depth
Rotational Movement of fault blocks



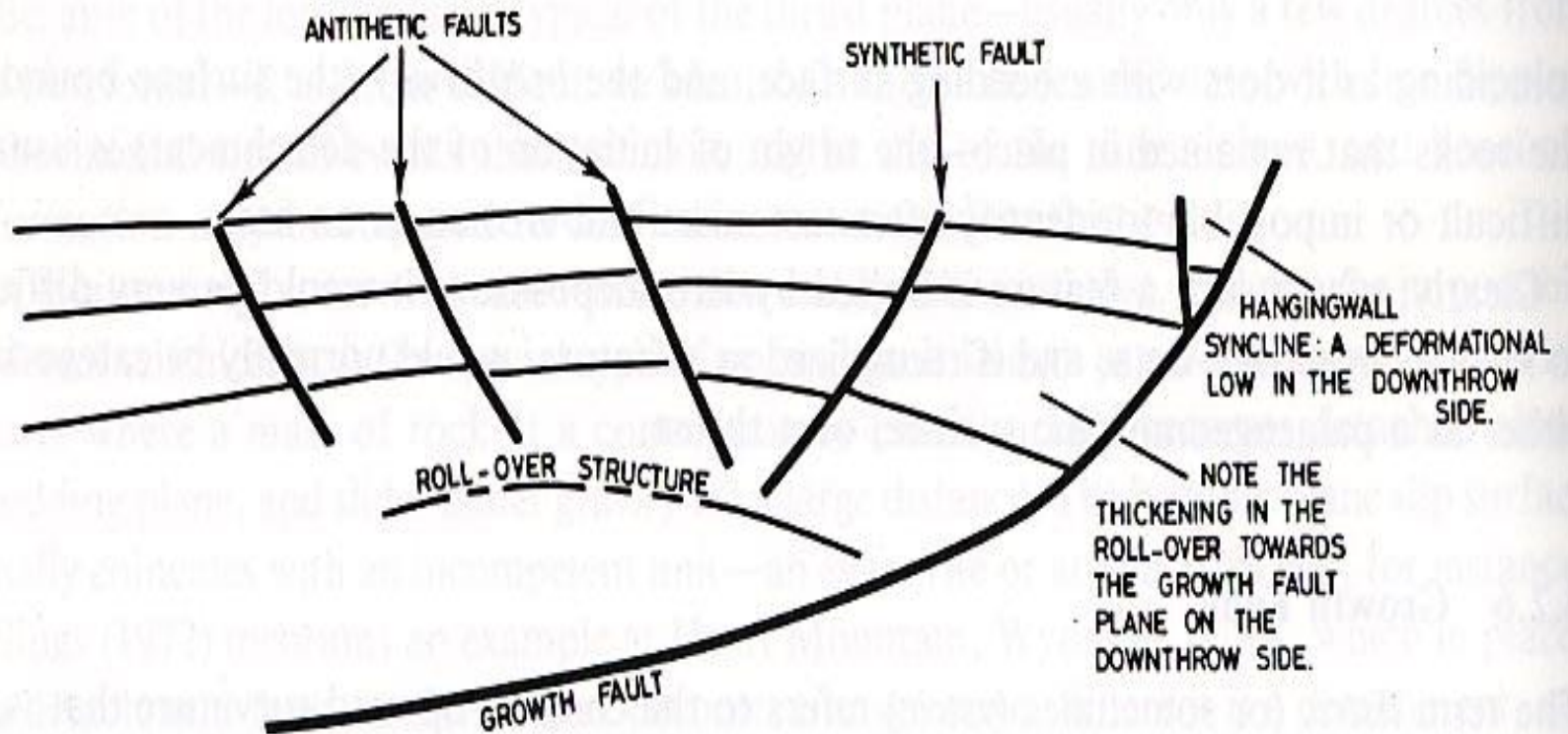
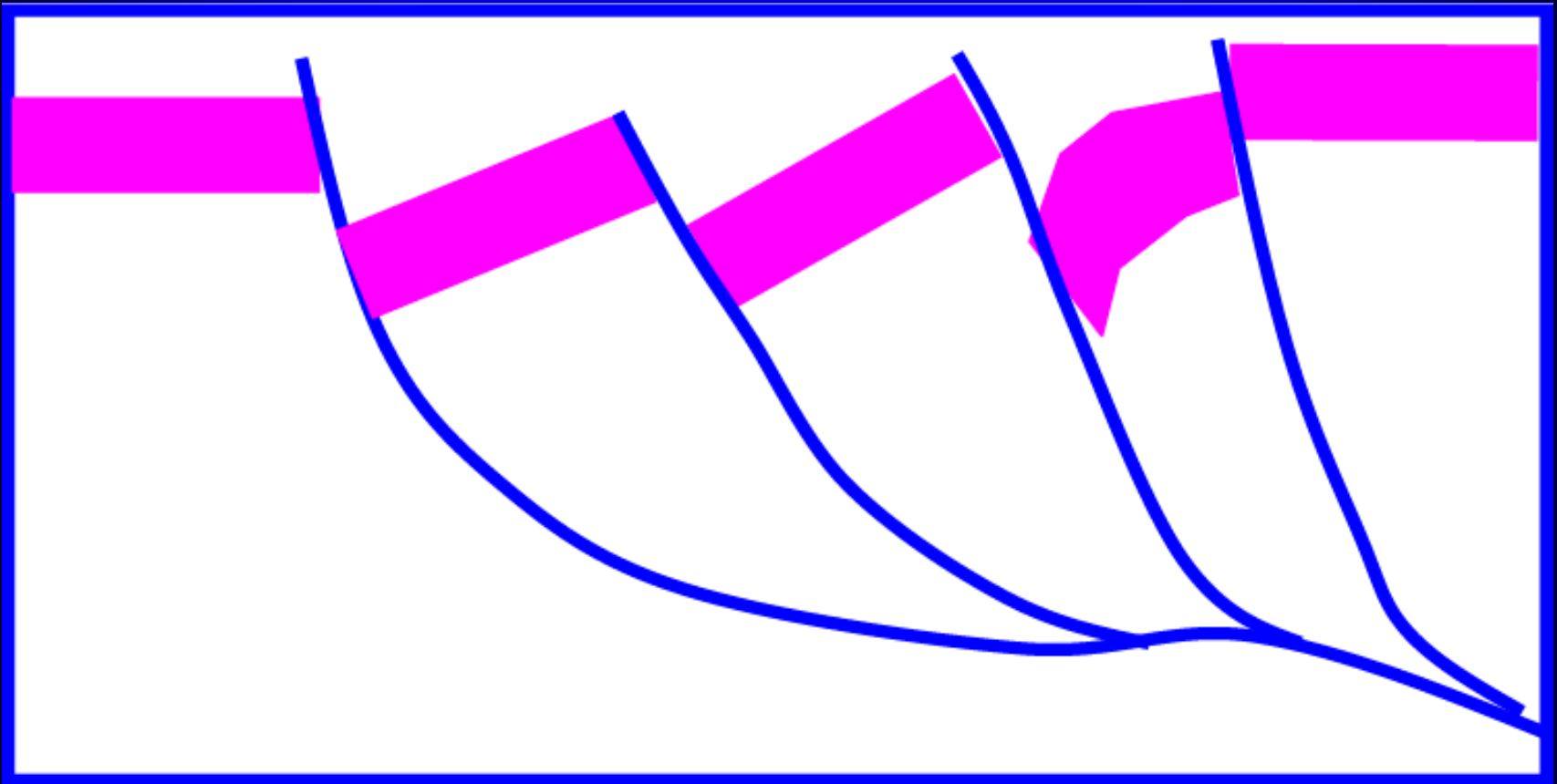
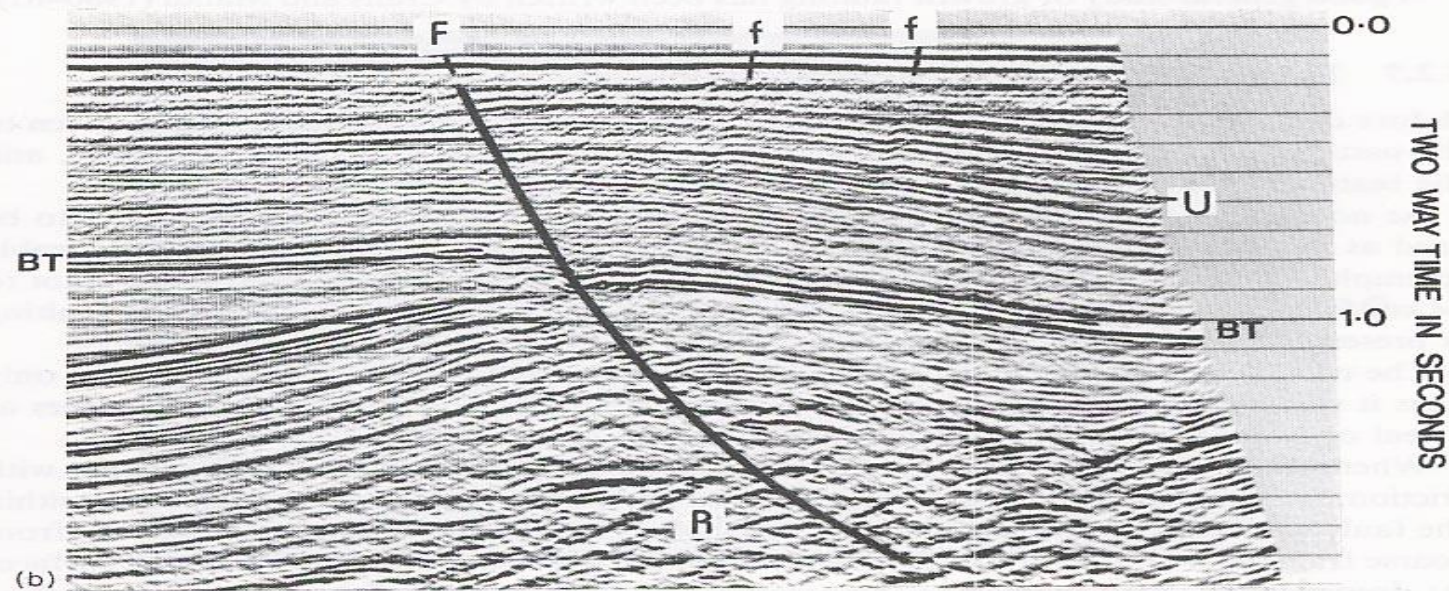
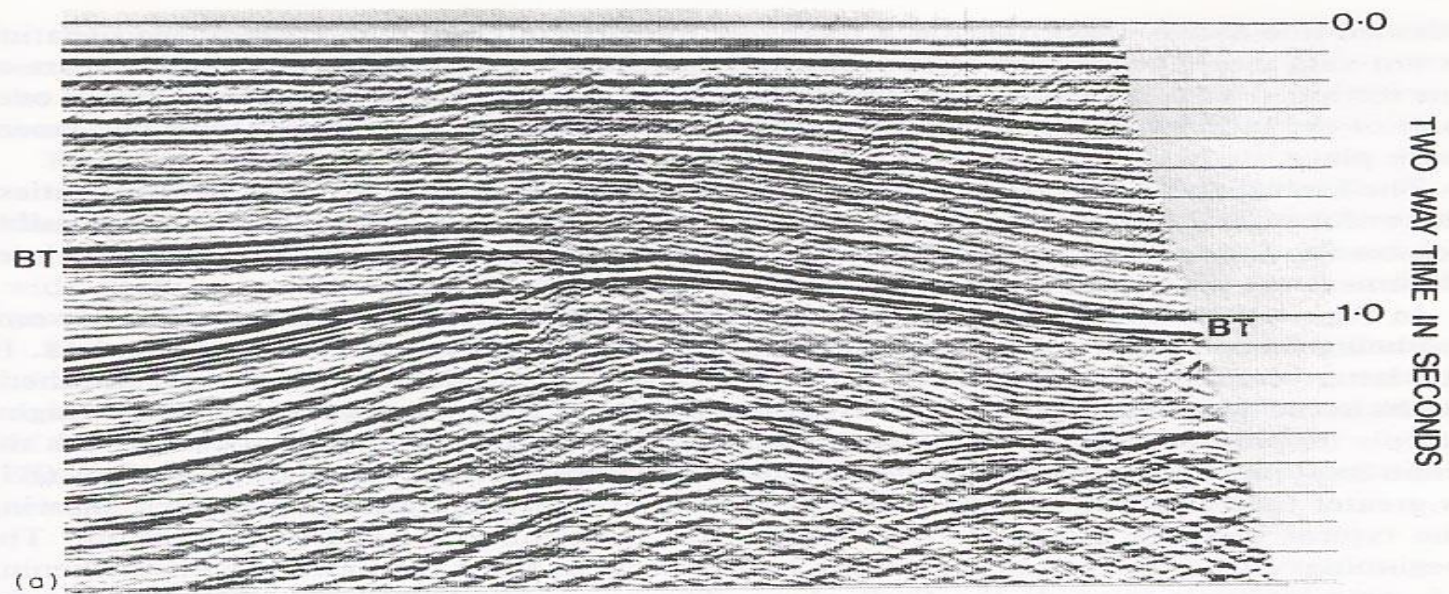


Fig. 4.8. Schematic section showing basic geometry and terminology of a growth fault

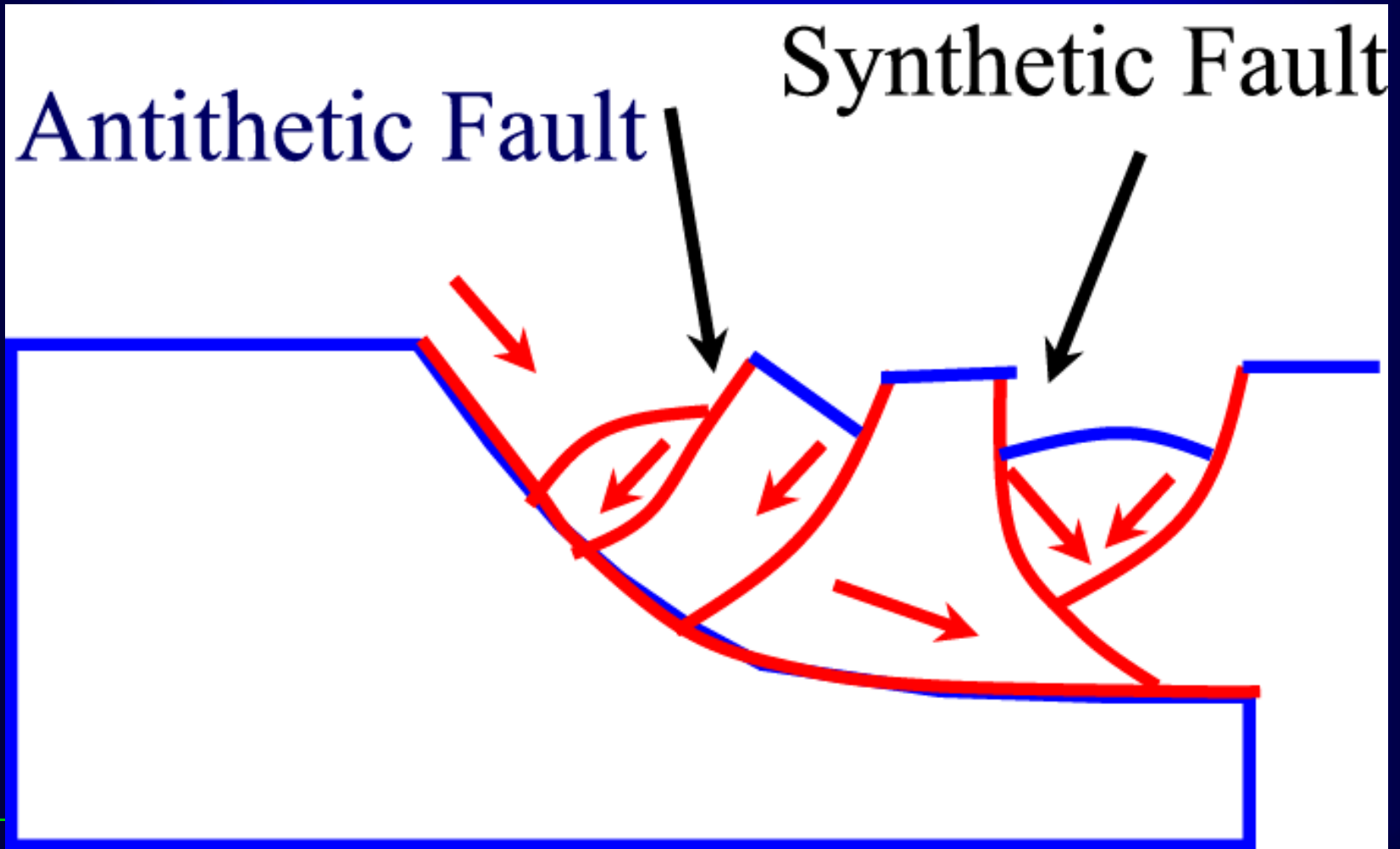
Detachment Systems-

**Listric rotational faults flatten with depth
Sole into sub-horizontal detachment**

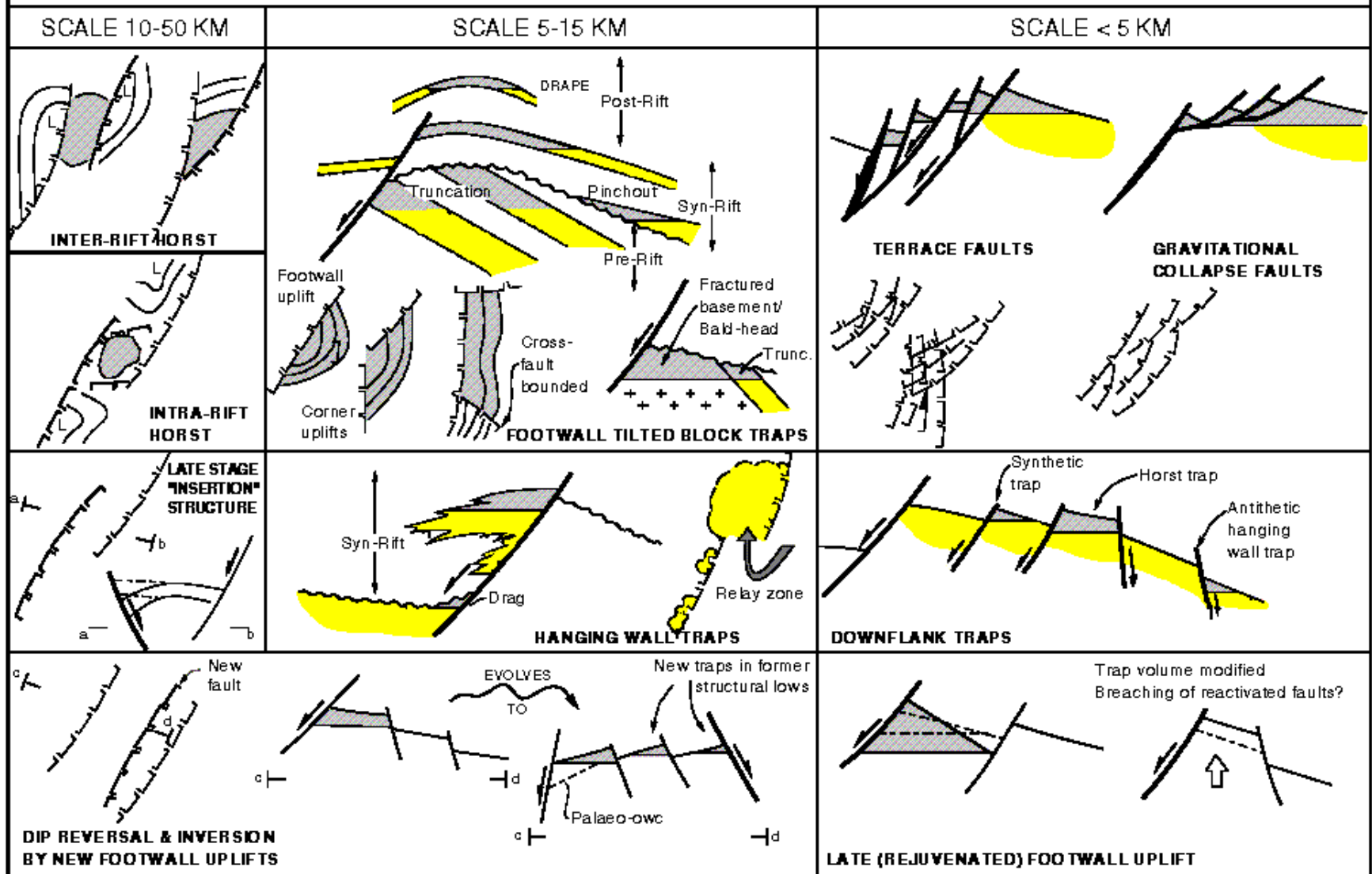


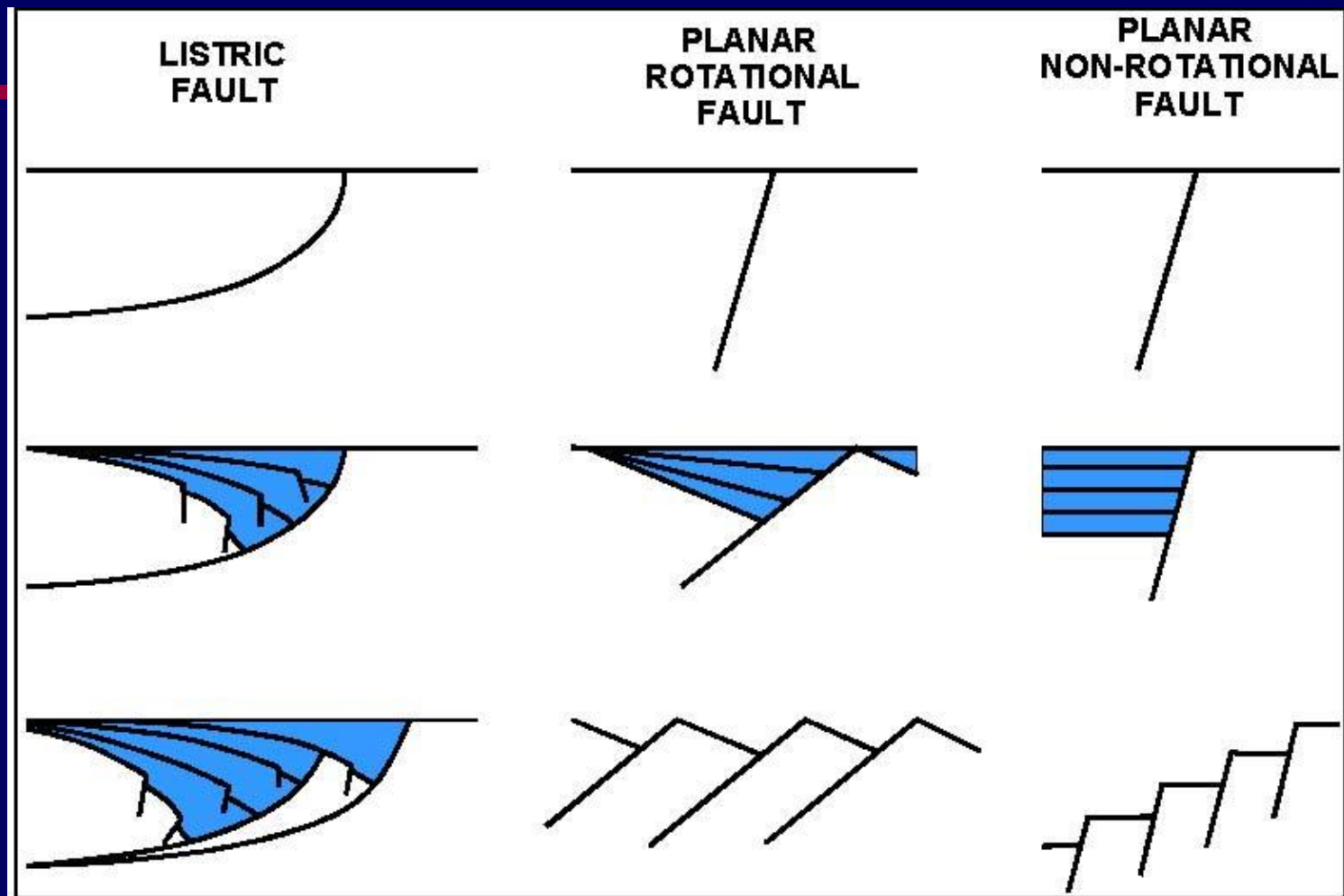


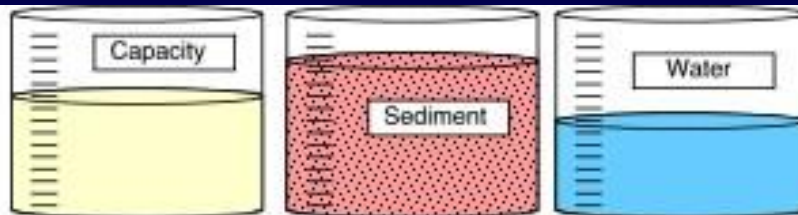
**Antithetic Faults-
Dip opposite to main fault**



TRAP STYLES IN RIFTS



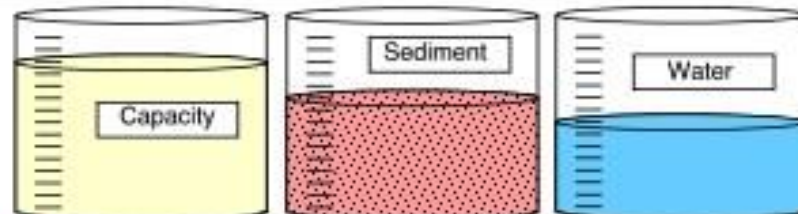
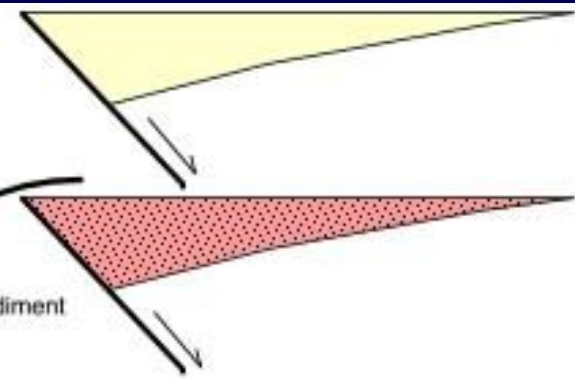




Example 1: Sediment supply > Capacity

- Basin is filled to capacity
- Deposited sediment = capacity
- Excess sediment leaves the system
- No large scale lakes are possible

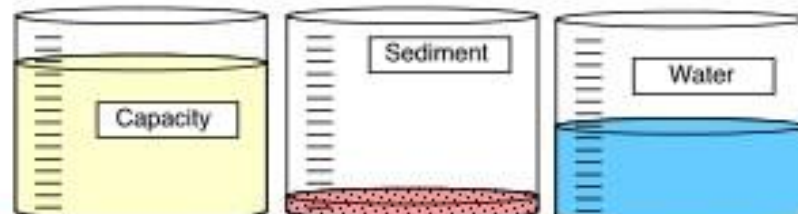
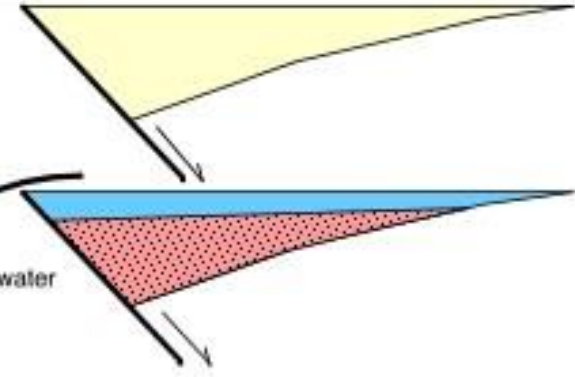
Excess sediment



Example 2: Capacity > Sediment Supply

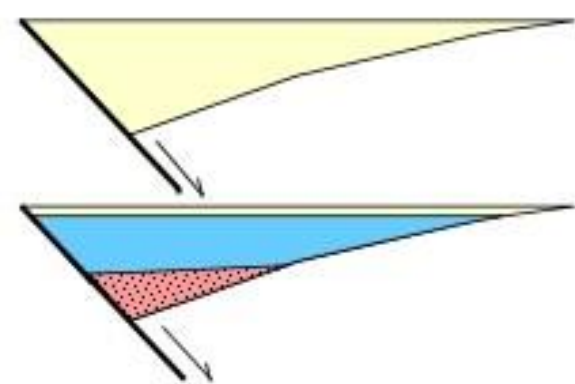
- Basin is underfilled
- Deposited sediment = sediment supply
- Available water > excess capacity
- Excess water leaves the system; lake is hydrologically open

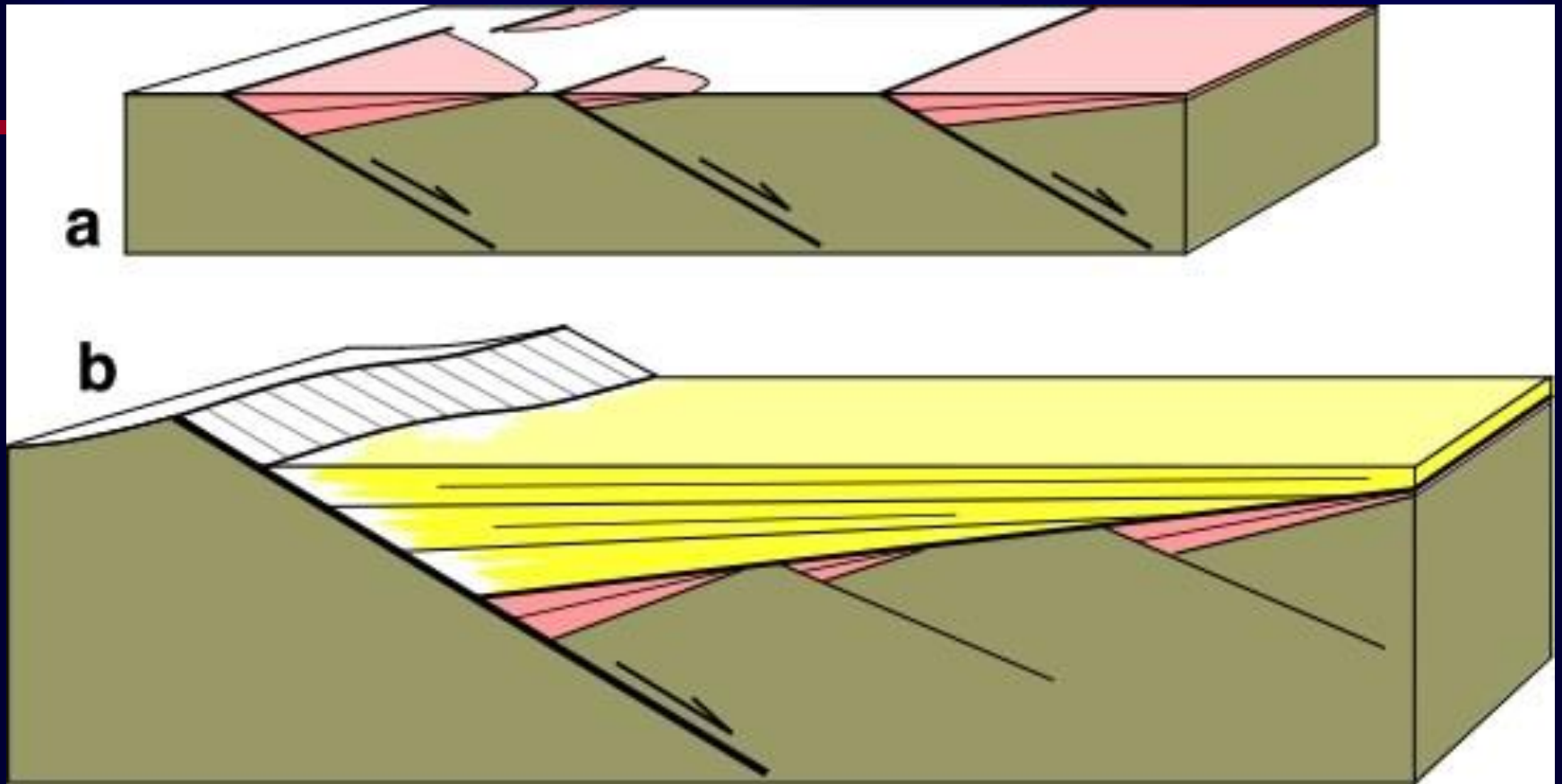
Excess water



Example 3: Capacity >> Sediment Supply

- Basin is underfilled
- Deposited sediment = sediment supply
- Available water < excess capacity
- All water remains in the system; lake is hydrologically closed



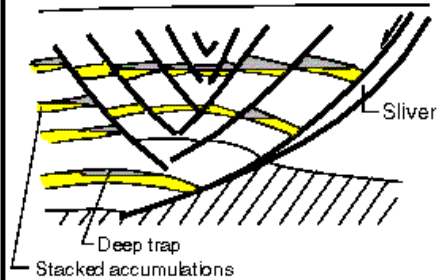


Stages in the evolution of a rift basin. (a) Early rifting associated with several minor, relatively isolated normal faults. (b) Mature rifting with through-going boundary fault zone, widespread deposition, and footwall uplift and erosion.

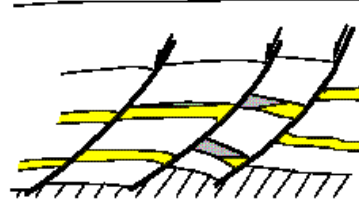
TRAP STYLES IN DELTA TECTONICS

LANDWARD POSITIONS - EXTENSIONAL TRAP TYPES

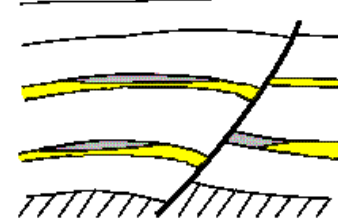
COLLAPSED CREST



SEQUENTIAL DOWN-TO-BASIN FAULTS

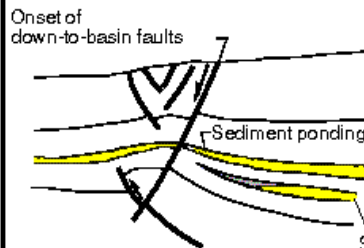


SIMPLE ROLLOVER

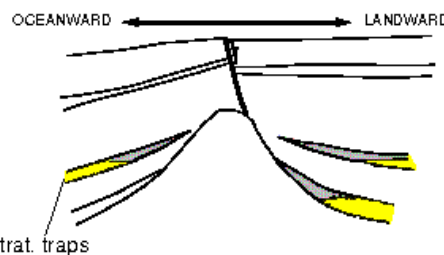


OCEANWARD & SLOPE POSITIONS - DIAPYRIC & COMPRESSIONAL TRAPS

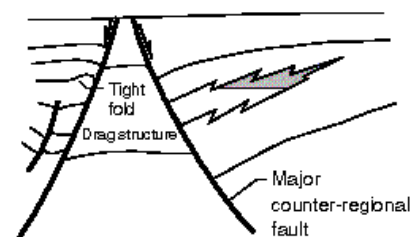
BURIED TOE THRUST



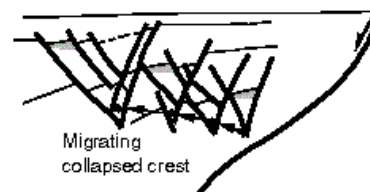
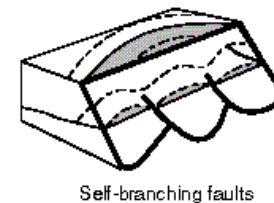
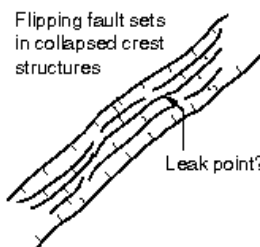
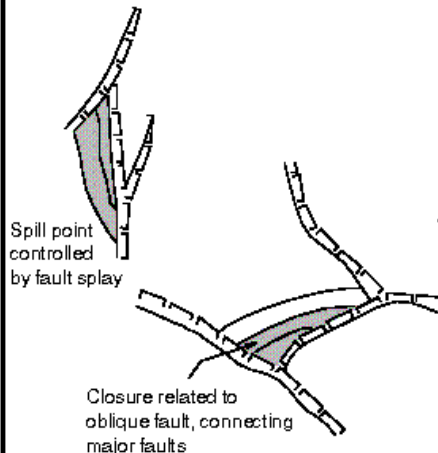
COUNTER-REGIONAL FAULT ABOVE SHALE DOME



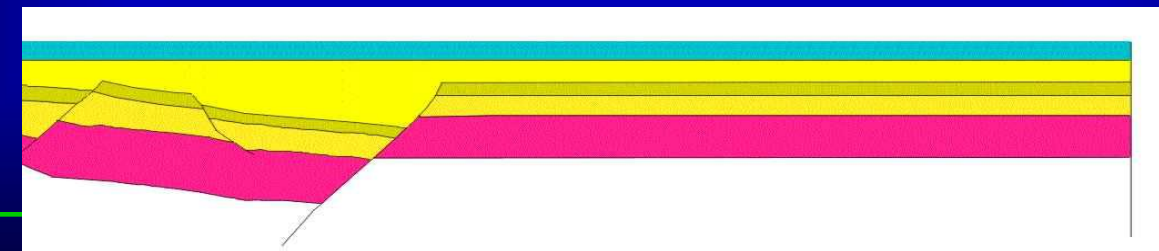
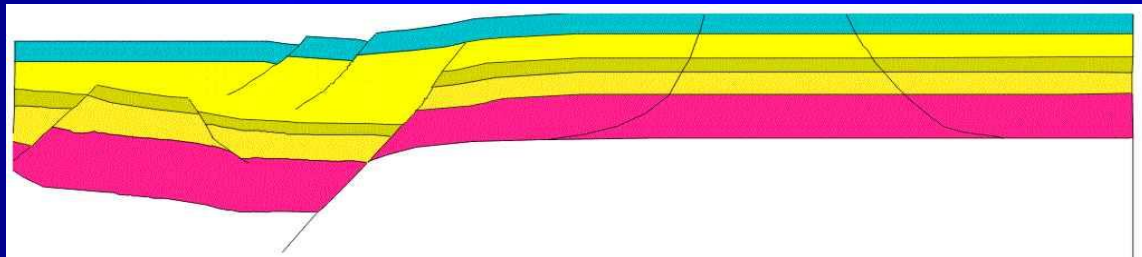
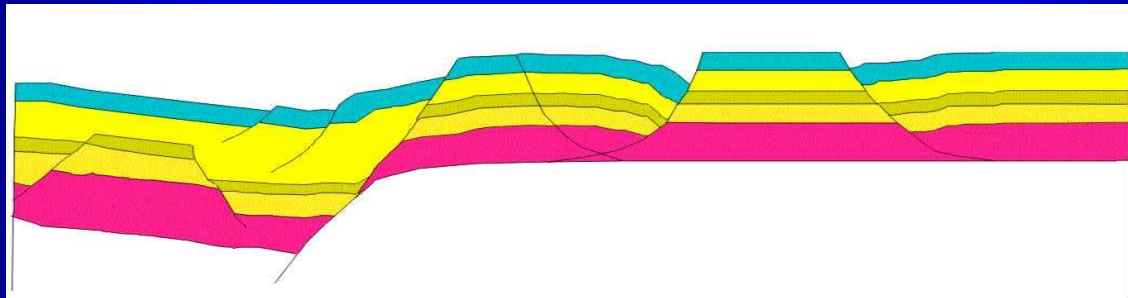
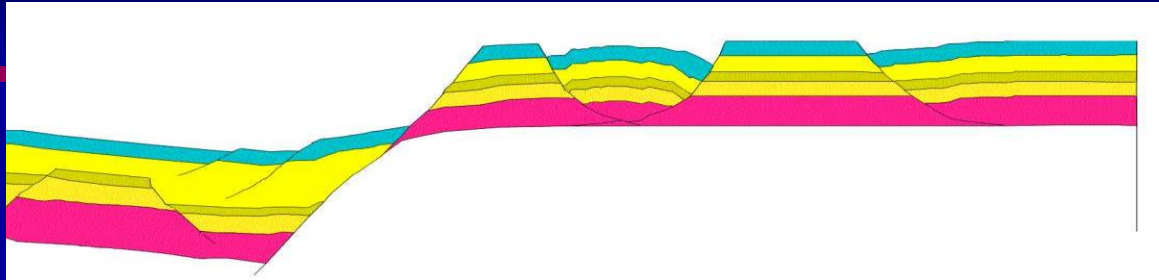
BACK-TO-BACK STRUCTURE



SPECIAL CASES

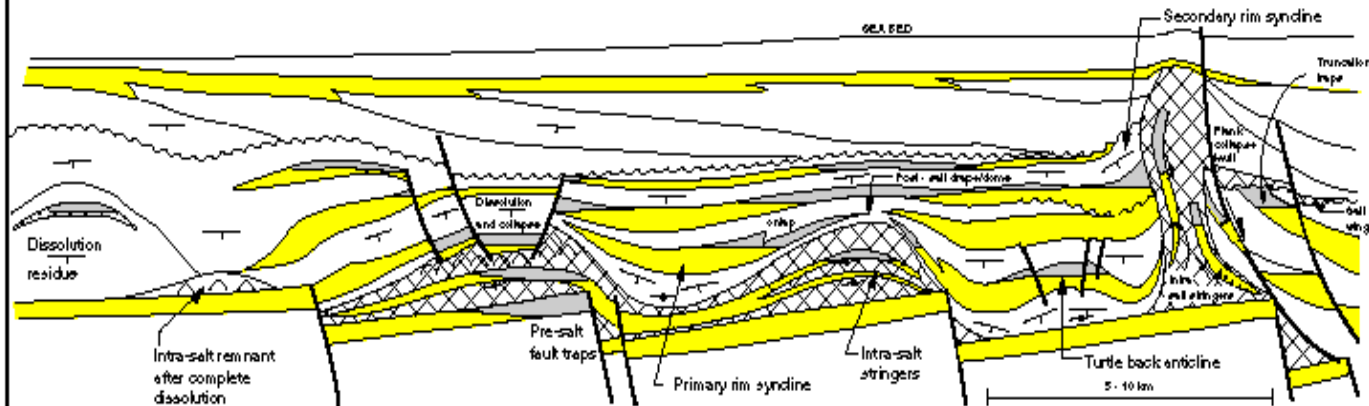


Hanging wall collapse versus foot wall collapse

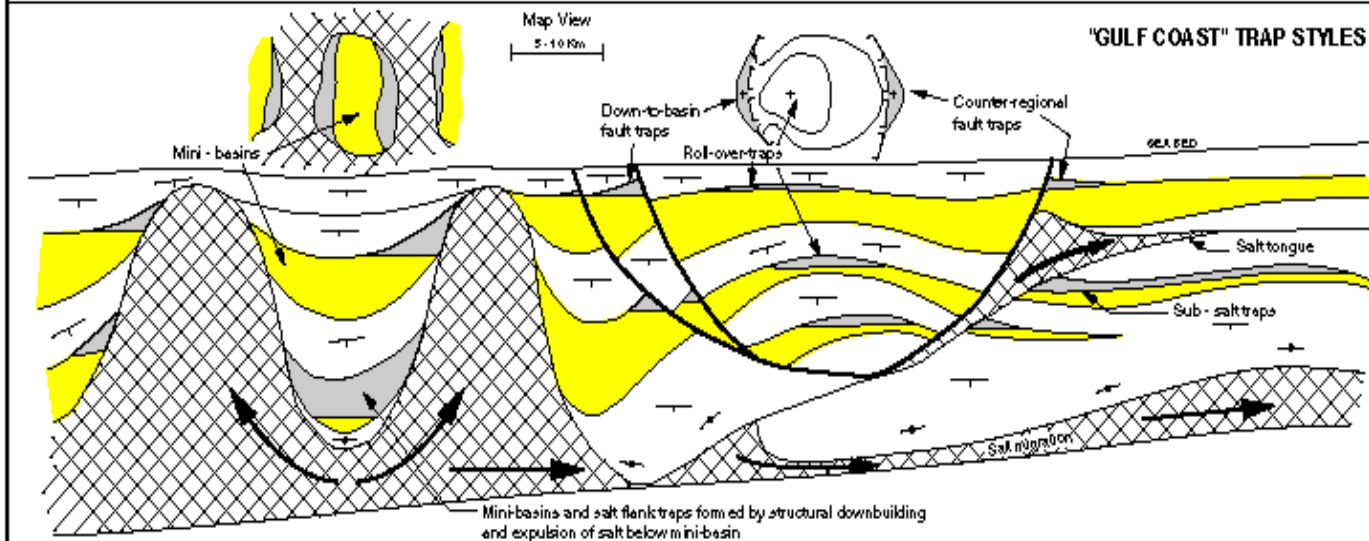


TRAP STYLES IN SALT TECTONICS

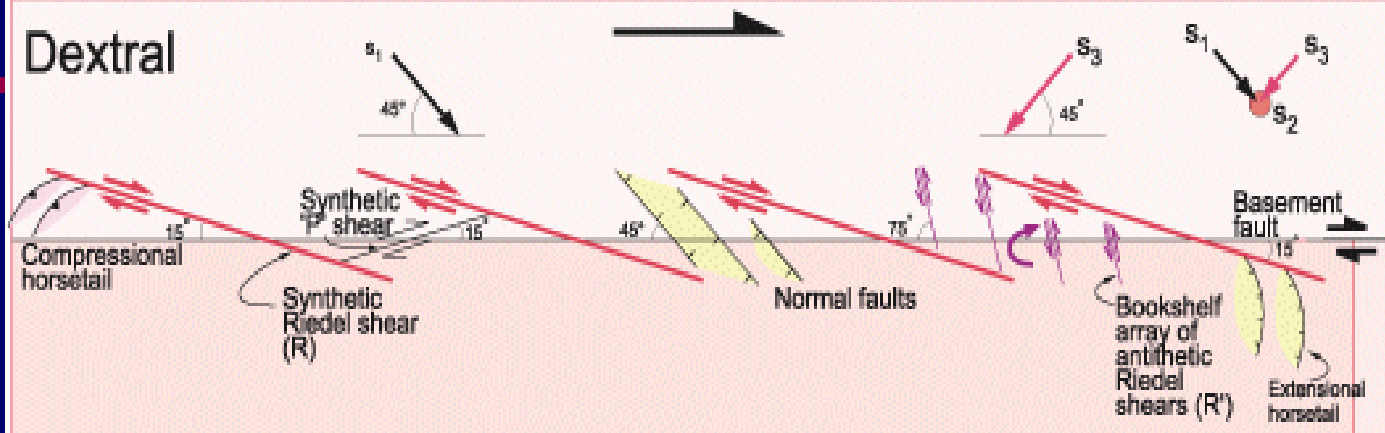
"TRADITIONAL" TRAP STYLES



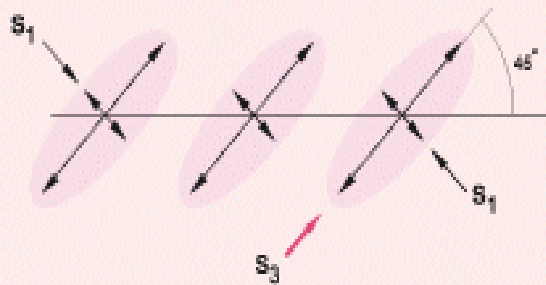
"GULF COAST" TRAP STYLES



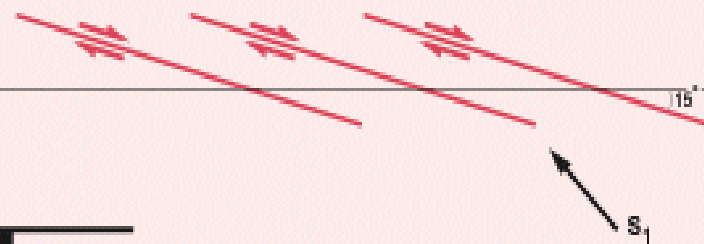
Dextral



En Echelon Folds

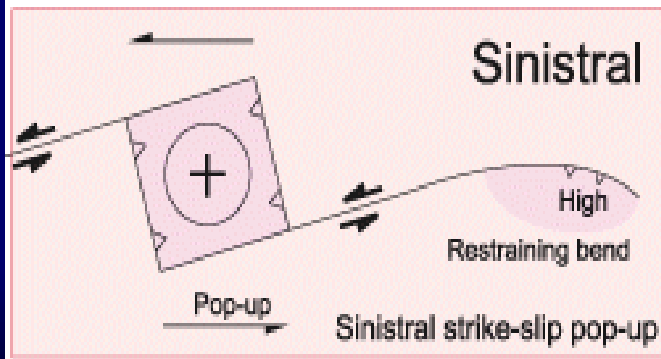


En Echelon Riedel Shears

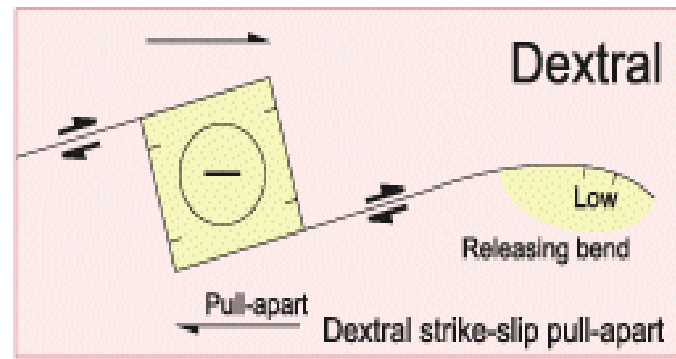


Dextral

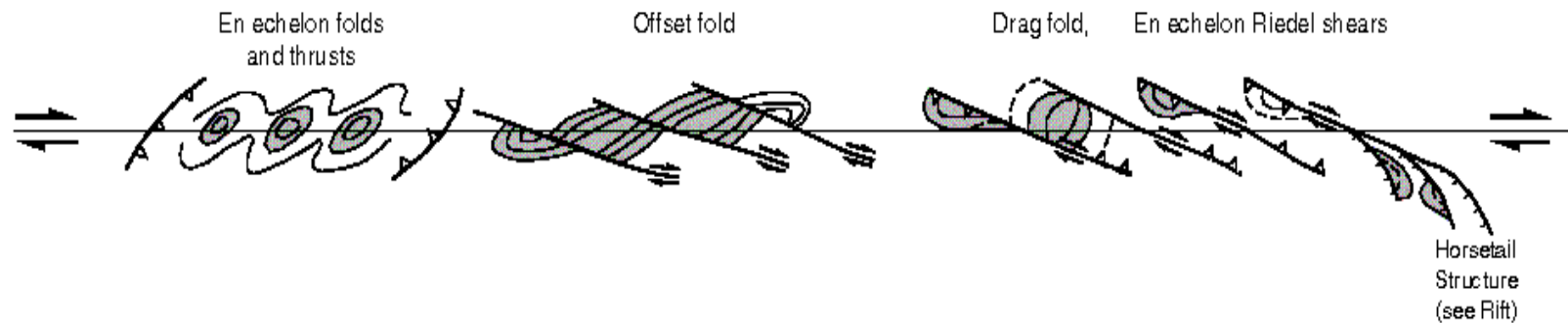
Sinistral



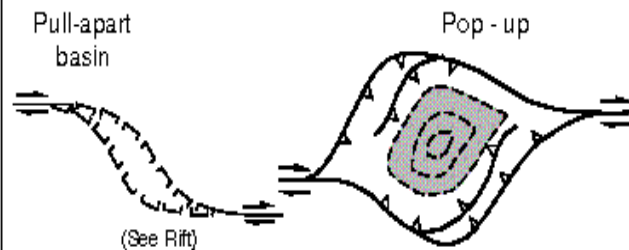
Dextral



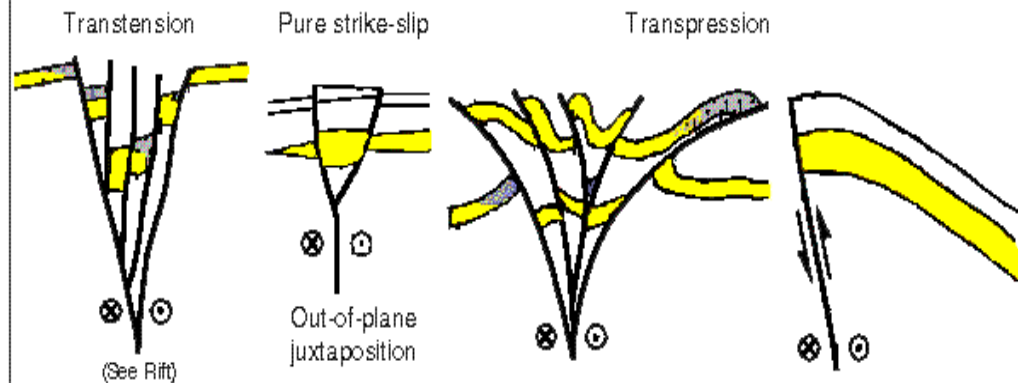
TRAP STYLES IN STRIKE-SLIP TECTONICS



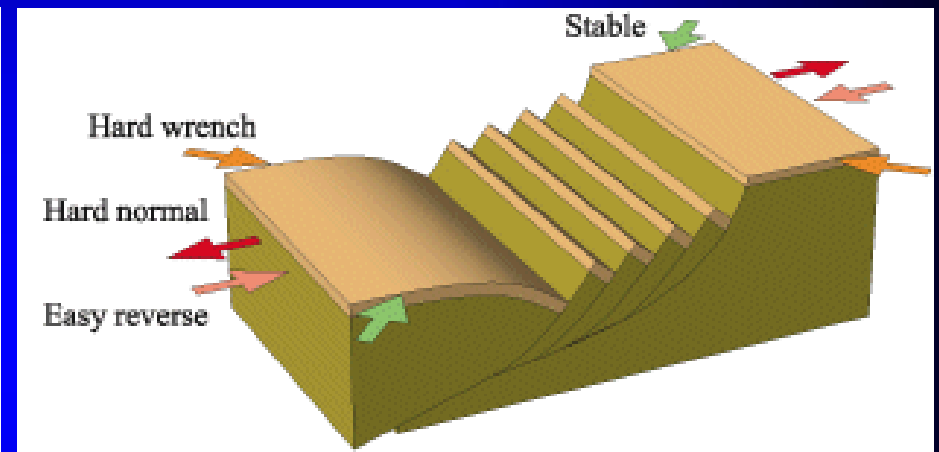
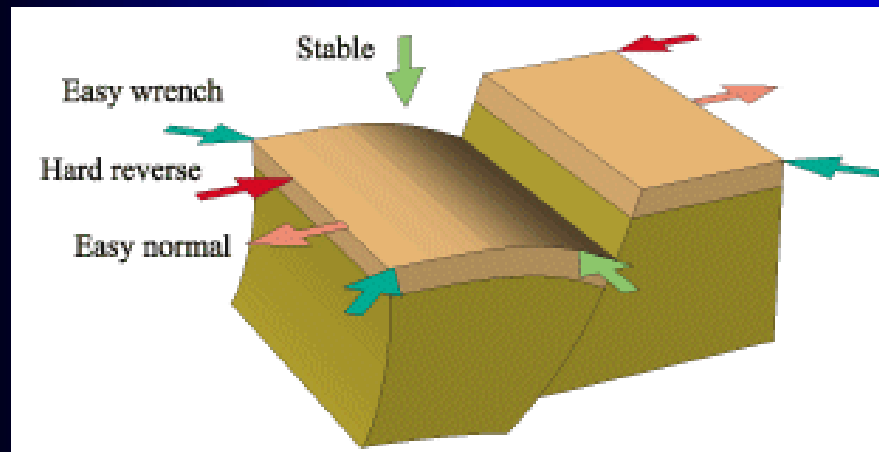
SINGLE DEEP-SEATED BASEMENT FAULT



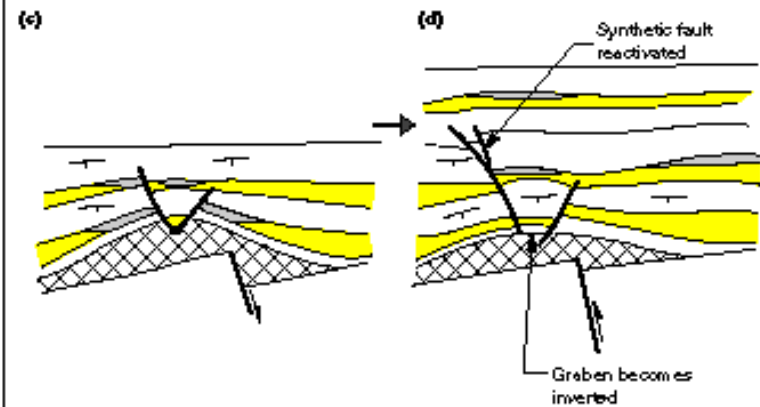
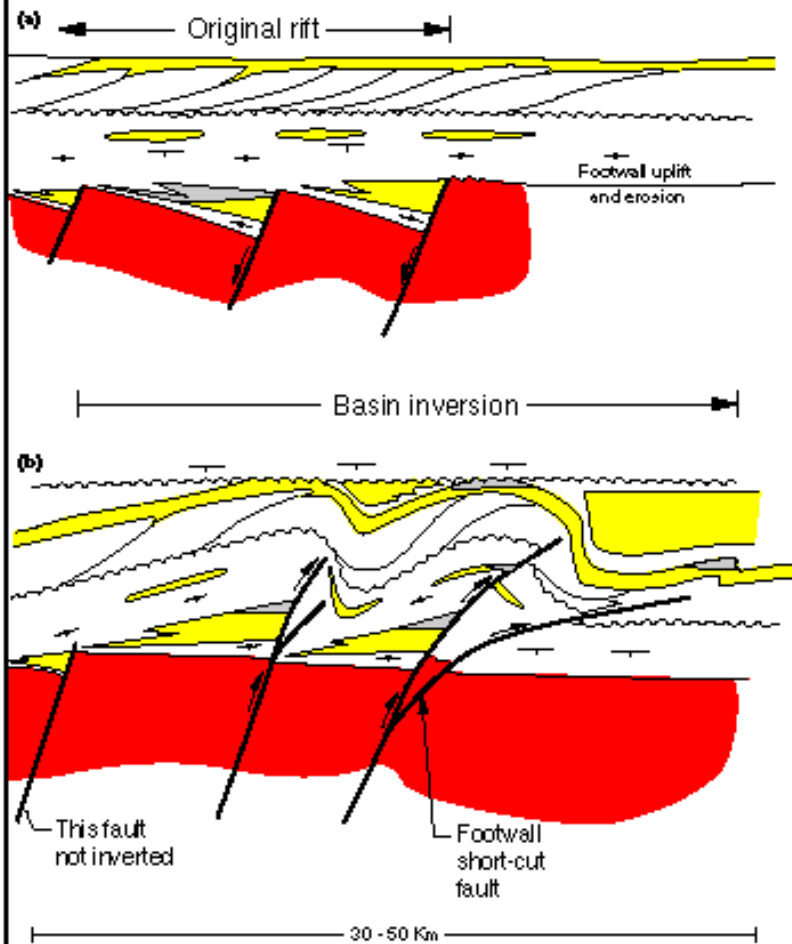
OFFSET WRENCH FAULTS



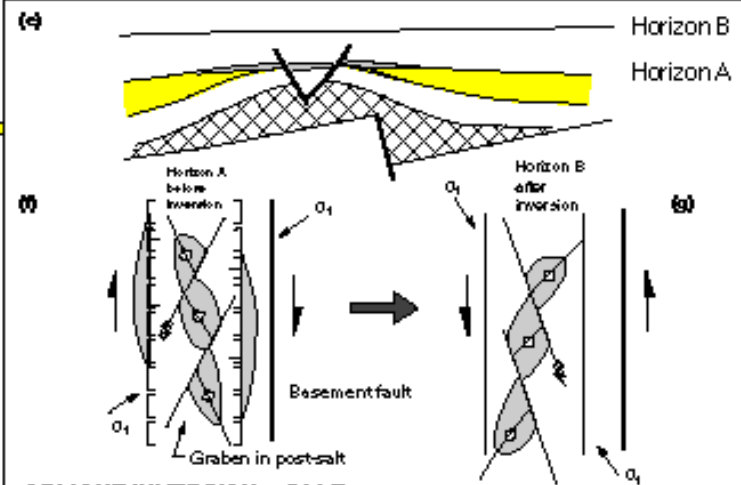
FLOWER STRUCTURES



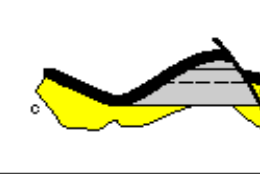
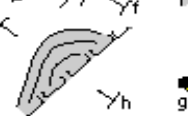
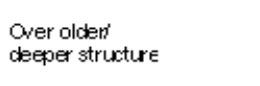
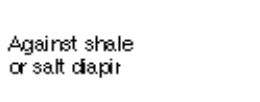
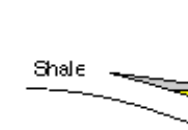
TRAP STYLES IN INVERSION TECTONICS



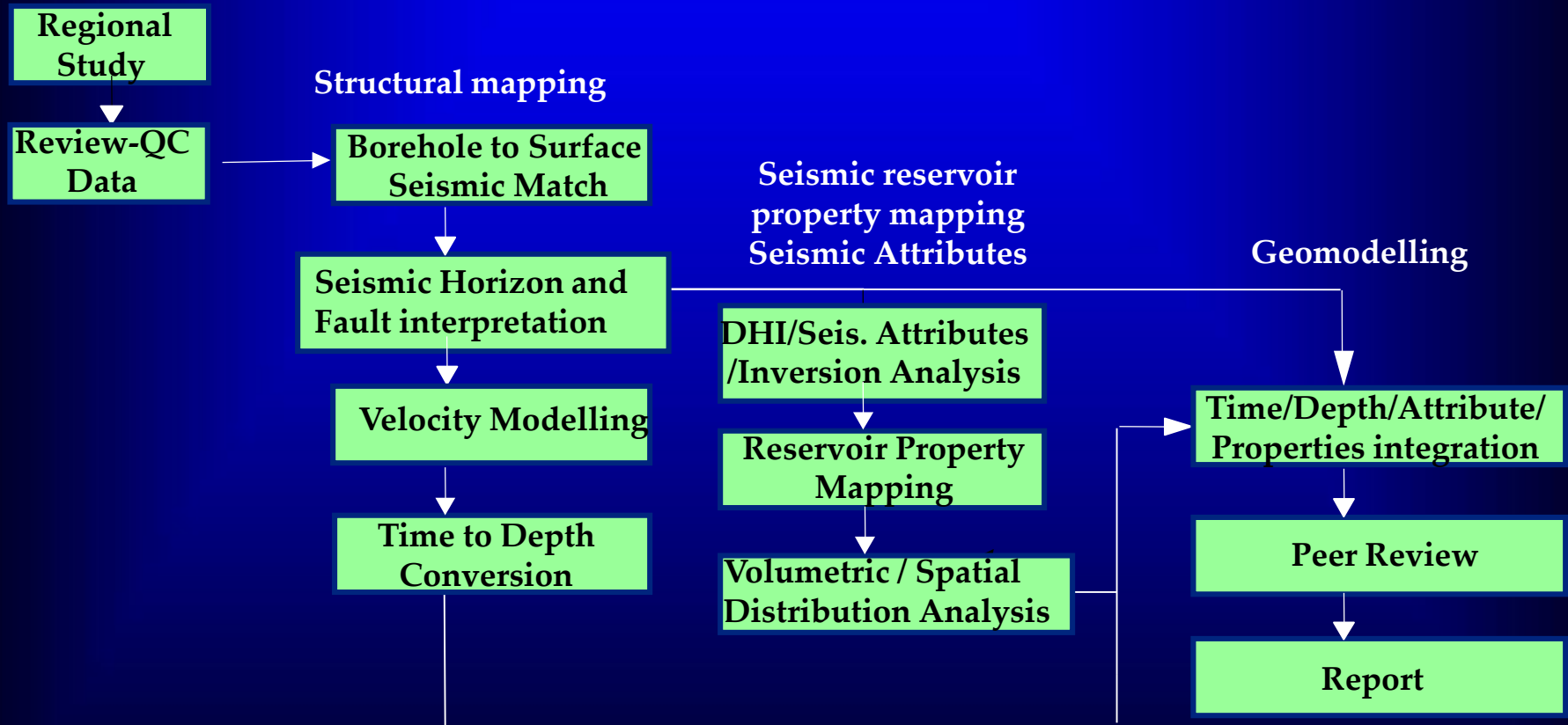
ORTHOGONAL INVERSION + SALT



OBLIQUE INVERSION + SALT

STRUCTURAL TRAPS	DIP CLOSURE			* Structural spill point
	FAULTED DIP CLOSURE			Fault throws $\ll$ structural closure, and $\ll$ top seal thickness
	FAULT-ENHANCED DIP CLOSURE			Leakpoint shallower than spillpoint unless fault seals
	FAULTED CLOSURE FOOTWALL			Fault seal required
	FAULTED CLOSURE HANGING WALL			Fault seal required
STRUCTURAL/STRATIGRAPHIC TRAPS	DRAPE			Over older/deeper structure
	STRUCTURAL TRUNCATION			Against shale or salt diapir
	EROSIONAL TRUNCATION			① HC-water contact if no seat seal ② HC-water contact with effective seat seal
	PINCH-OUT			Some element of structural or dip closure still required
STRATIGRAPHIC TRAPS	ISOLATED SAND BODY			
	REEF			

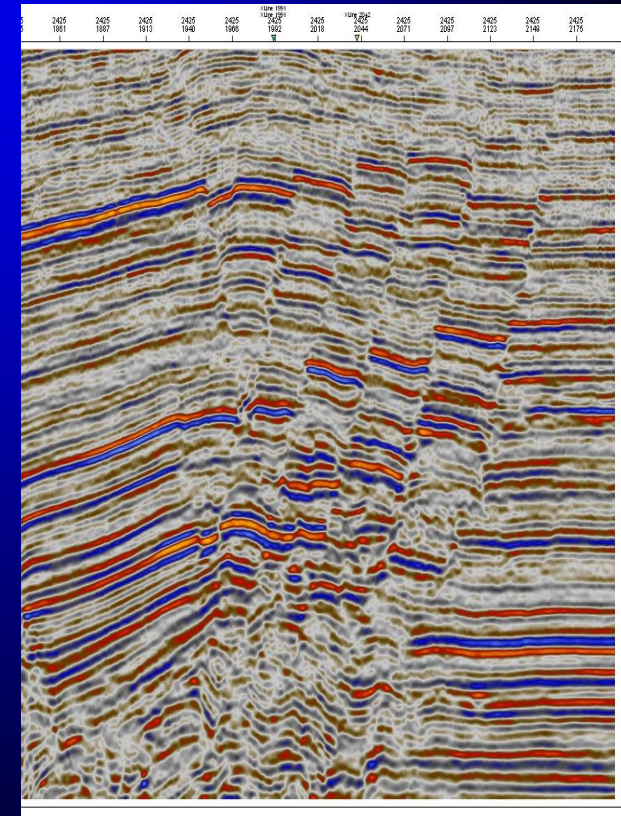
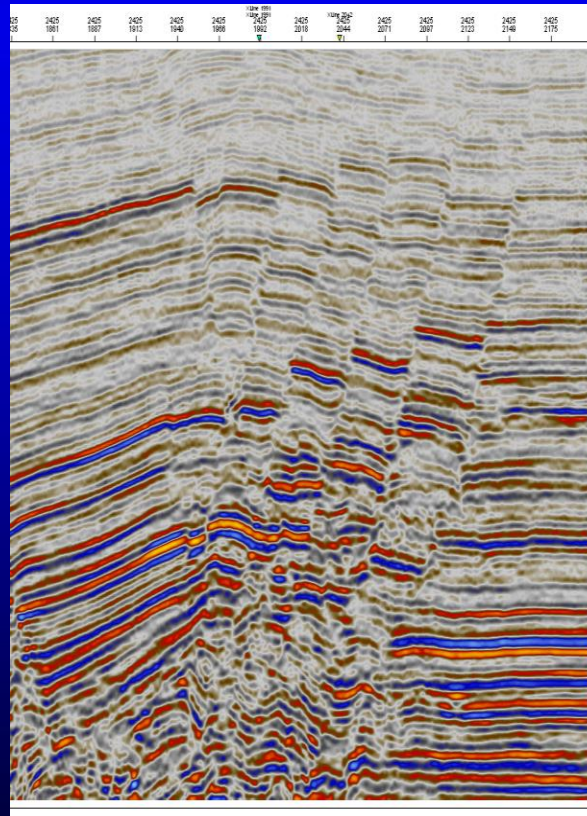
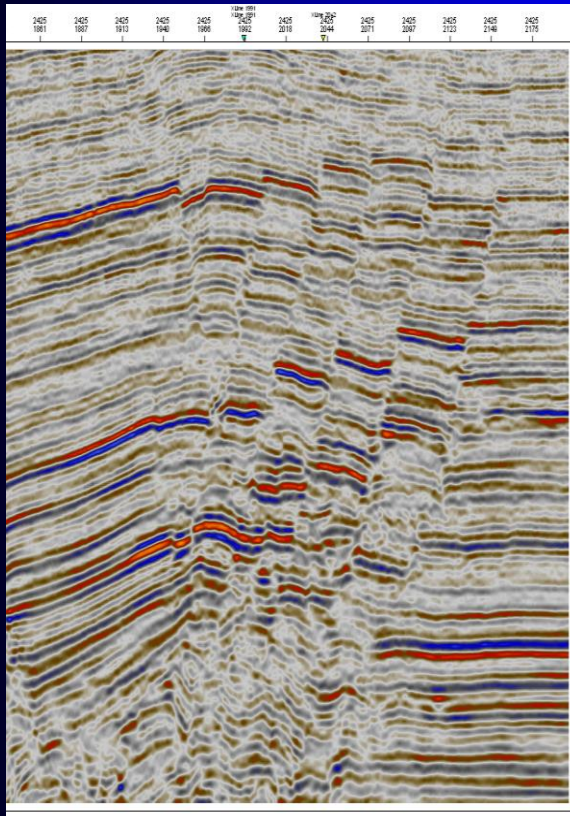
Interpretation Workflow



Initial Questions

Amplitude Fidelity and Filtering

AGC effect on data: good for interpretation and bad for attributes and reservoir characterization



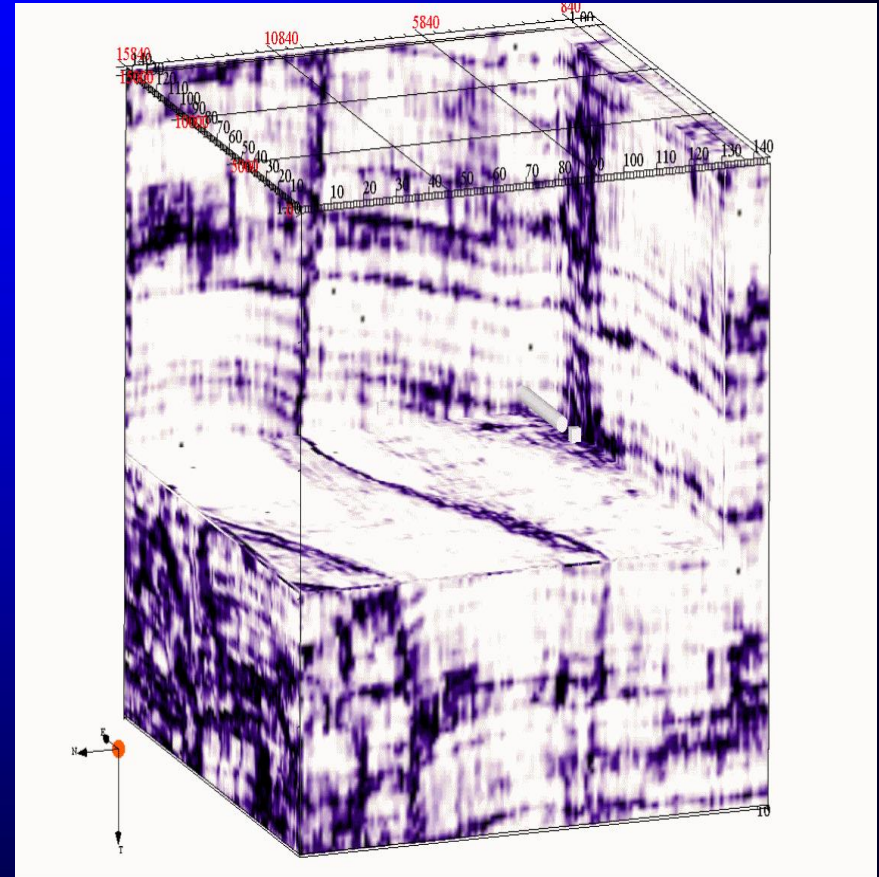
Original Amplitude

Time Gain

AGC filter

Seismic Attributes

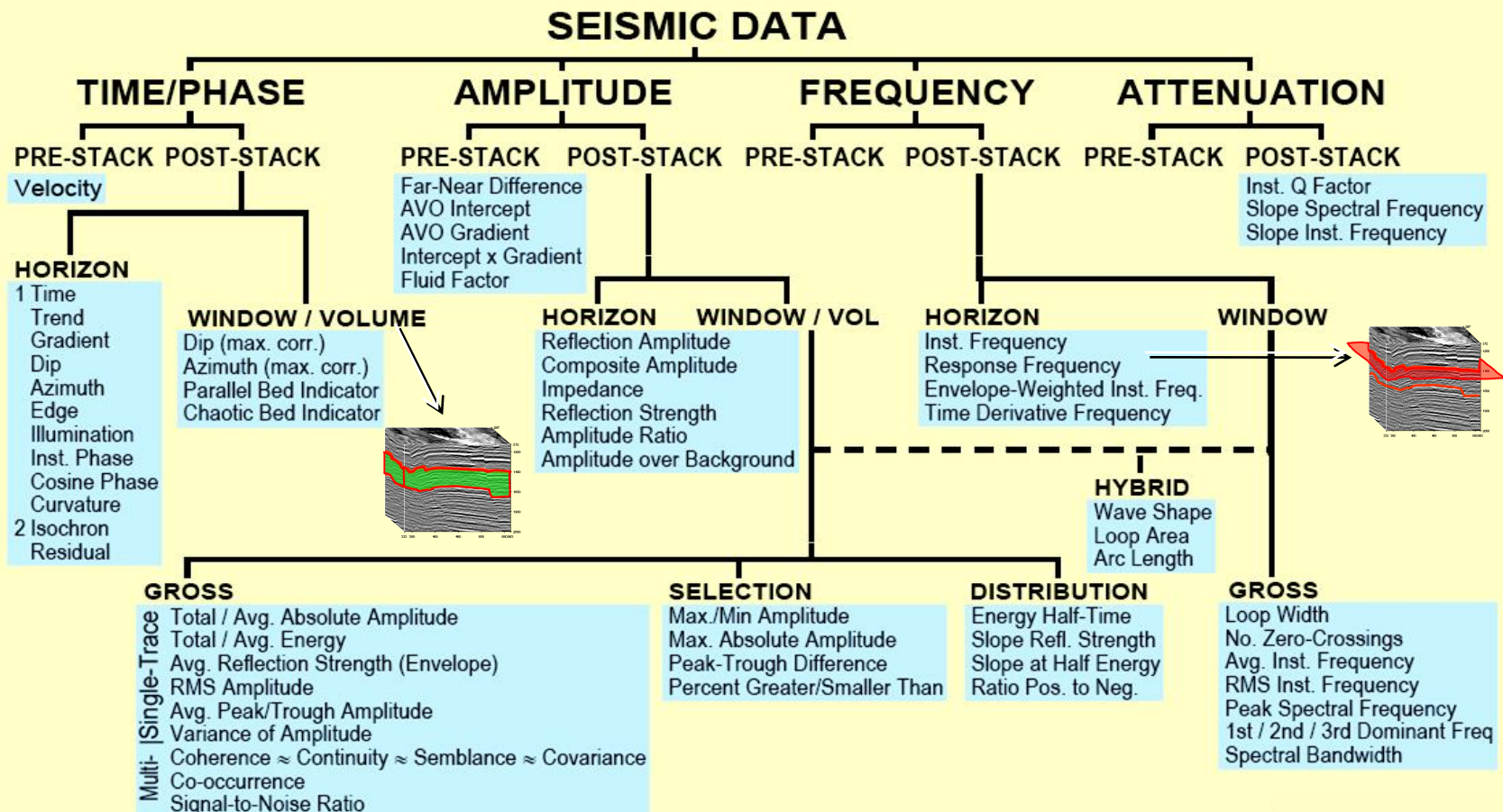
- Seismic attributes are all the information obtained from seismic data, either by direct measurements or by logic or experienced-based reasoning.
- The main objective of the attributes is to provide detailed and accurate information to the interpreter on structural, stratigraphic and lithological parameters of the seismic prospect.



Seismic Attributes

- Pre stack:
 - Input data is CDP or image gathers
 - Have directional (azimuth) and offset related information
 - Lots of information that may not be practical in initial or basic studies
 - Contain considerable amounts of data that can be directly related to fluid content and fracture orientation.
 - AVO, velocities, azimuthal are the most prominent of this class.
- Post stack
 - After data is stacked, these are computed on the trace.

Seismic Attributes General classification

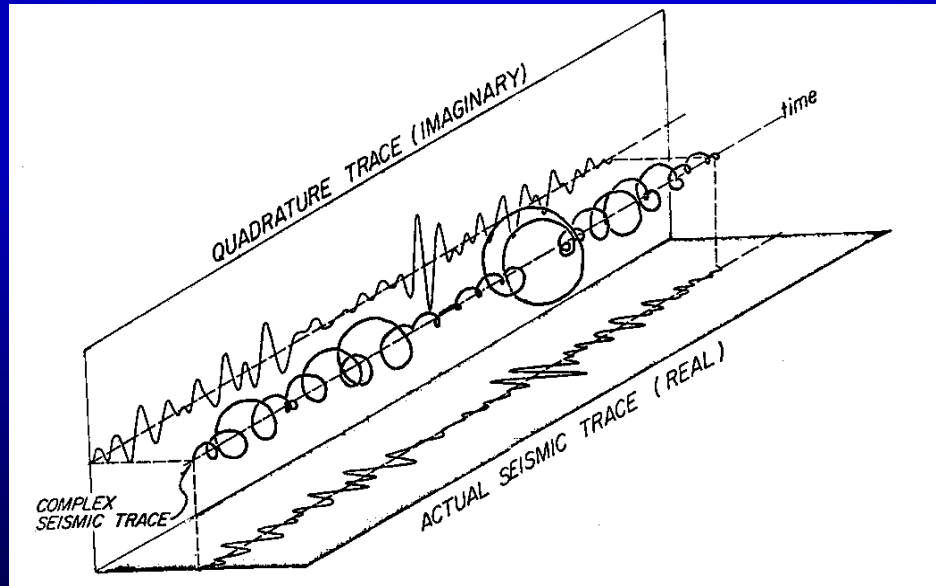


From A.R. Brown

Seismic Attributes

- Seismic attributes:
 - Properties of the seismic trace when thought of as an analytic (complex) trace with both real and imaginary parts

Quadrature:
imaginary part
seismic trace from
Hilbert transform



Real:
conventional
seismic trace

Hilbert transform $\longrightarrow$ complex trace from the Real seismic trace

Seismic Attributes

Instantaneous Attributes

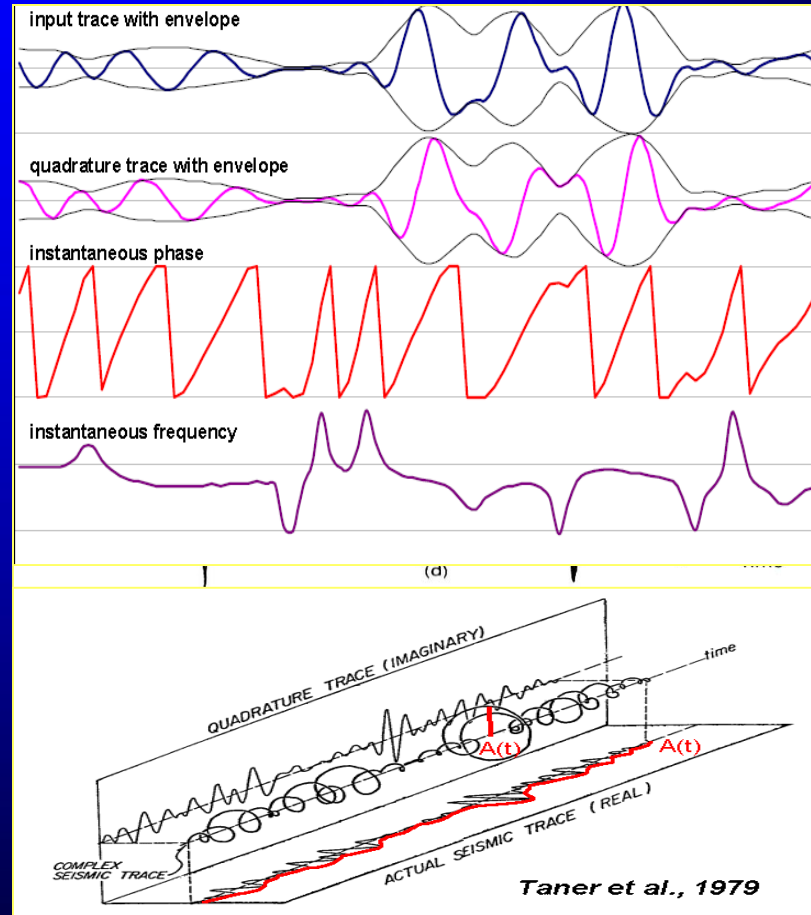
Input Trace with envelope

Quadrature trace with envelope

Instantaneous Phase

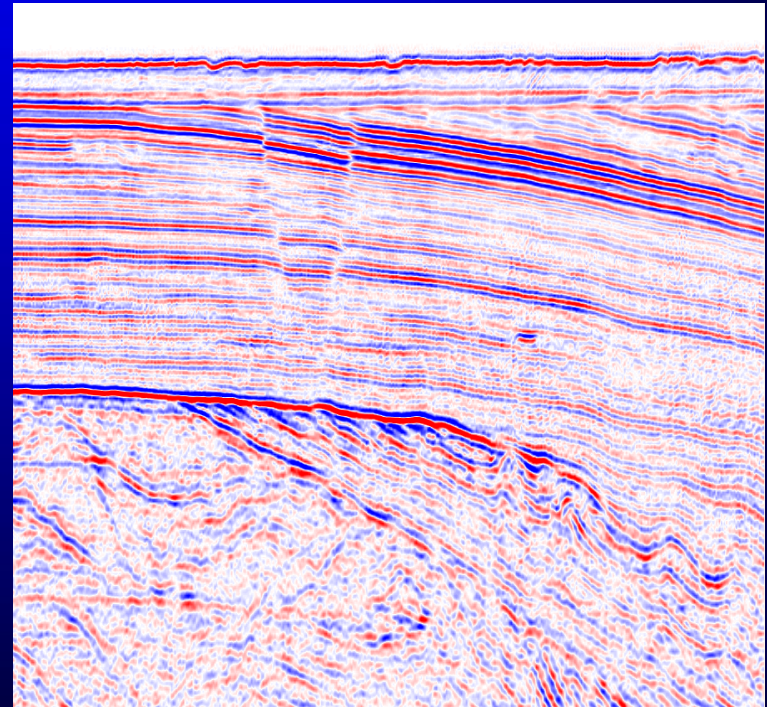
Instantaneous Frequency

Envelope attribute also called
instantaneous amplitude or
reflection strength Frequency



Display and use of Seismic Attributes

- Seismic Amplitude:
 - Trace's amplitude value at the horizon time/depth
 - Identify bright spots/dim spots



Display and use of Seismic Attributes

Seismic Amplitude:

- Represents mainly the acoustic impedance contrast, hence reflectivity,
- Bright spots,
- Possible gas accumulation,
- Sequence boundaries,
- Thin-bed tuning effects
- Unconformities,
- Major changes of lithology,
- Major changes in depositional environment,
- Lateral changes indicating faulting,
- Spatial correlation to porosity and other lithologic variations,
- Indicates the group, rather than phase component of the seismic wave propagation,

Seismic Attributes

Instantaneous Amplitude

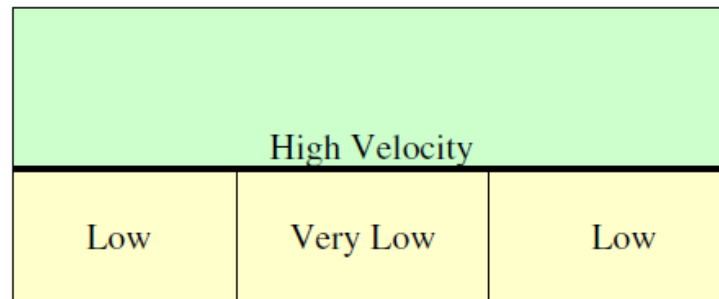
- **Bright spot** : It is associated with strong amplitude contrast across lithologies and their fluid (oil, gas and water) content.
- **Dim spot**: It is associated with weak amplitude contrast across lithologies and their fluid (oil, gas and water) content.
- **Flat spot**: Associated with fluid contact.

Seismic Stratigraphy

Bright Spots

Estimation of lithology
Estimation of porosity
Fluid content

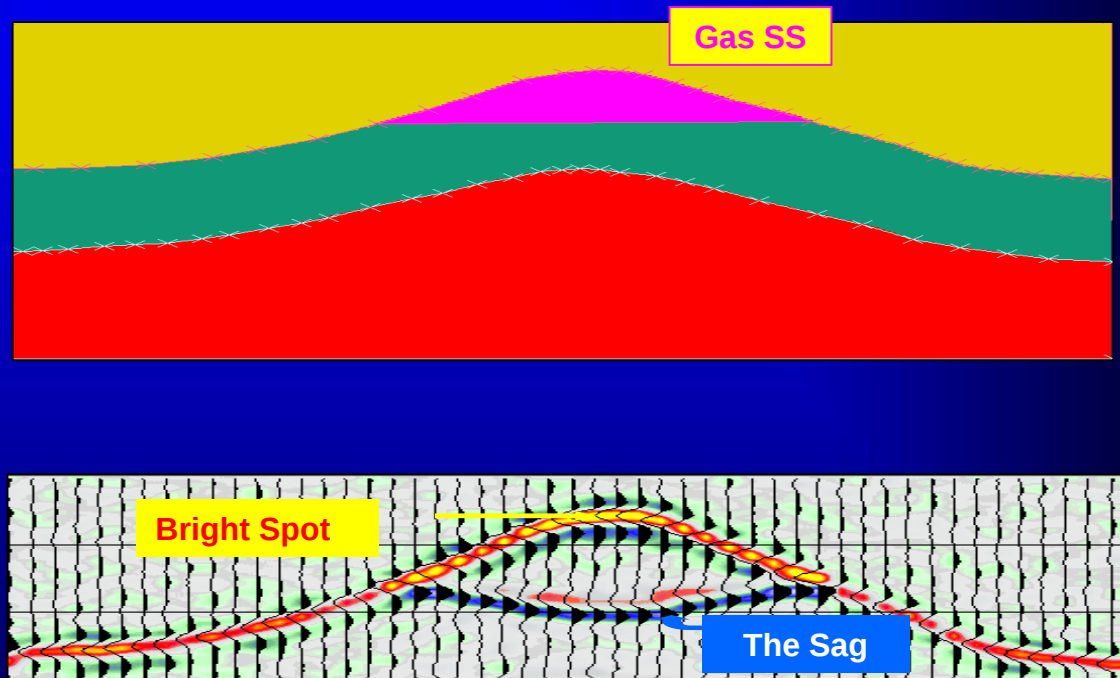
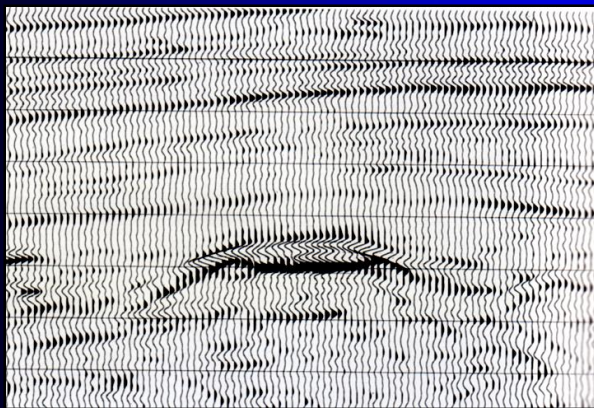
Bright spots



Usually, a 'bright spot' associated with gas has a negative RC.

Seismic Attributes

Amplitude-Bright Spot

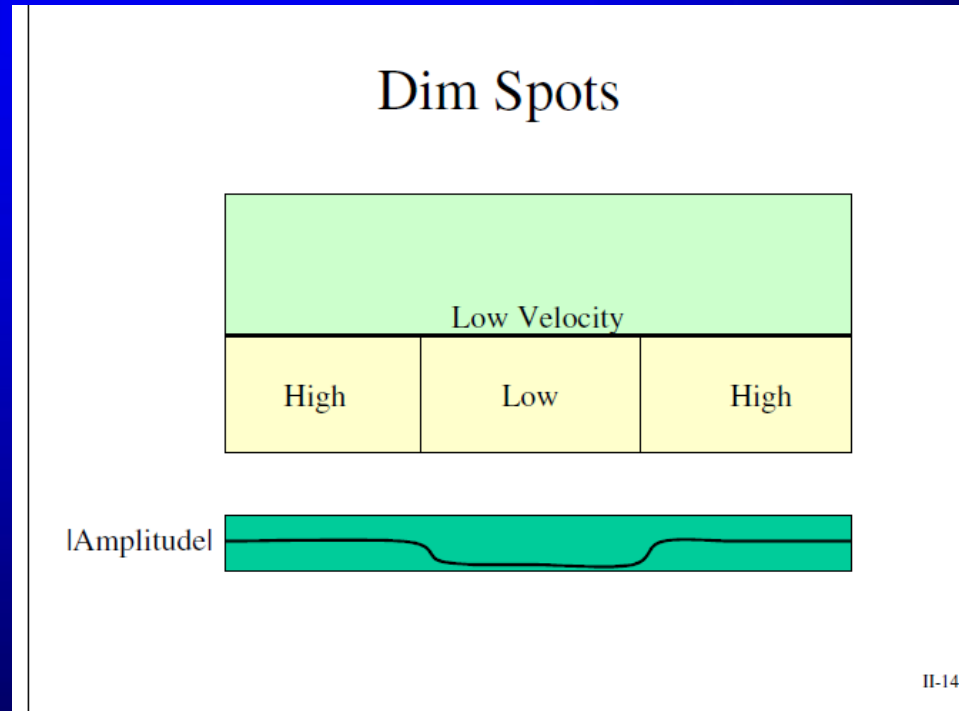


Not all Bright Spot prospects are as obvious as this simple model, but the idea is the same, and most are as subtle as a migraine.

Seismic Stratigraphy

Dim Spots

Estimation of lithology
Estimation of porosity
Fluid content

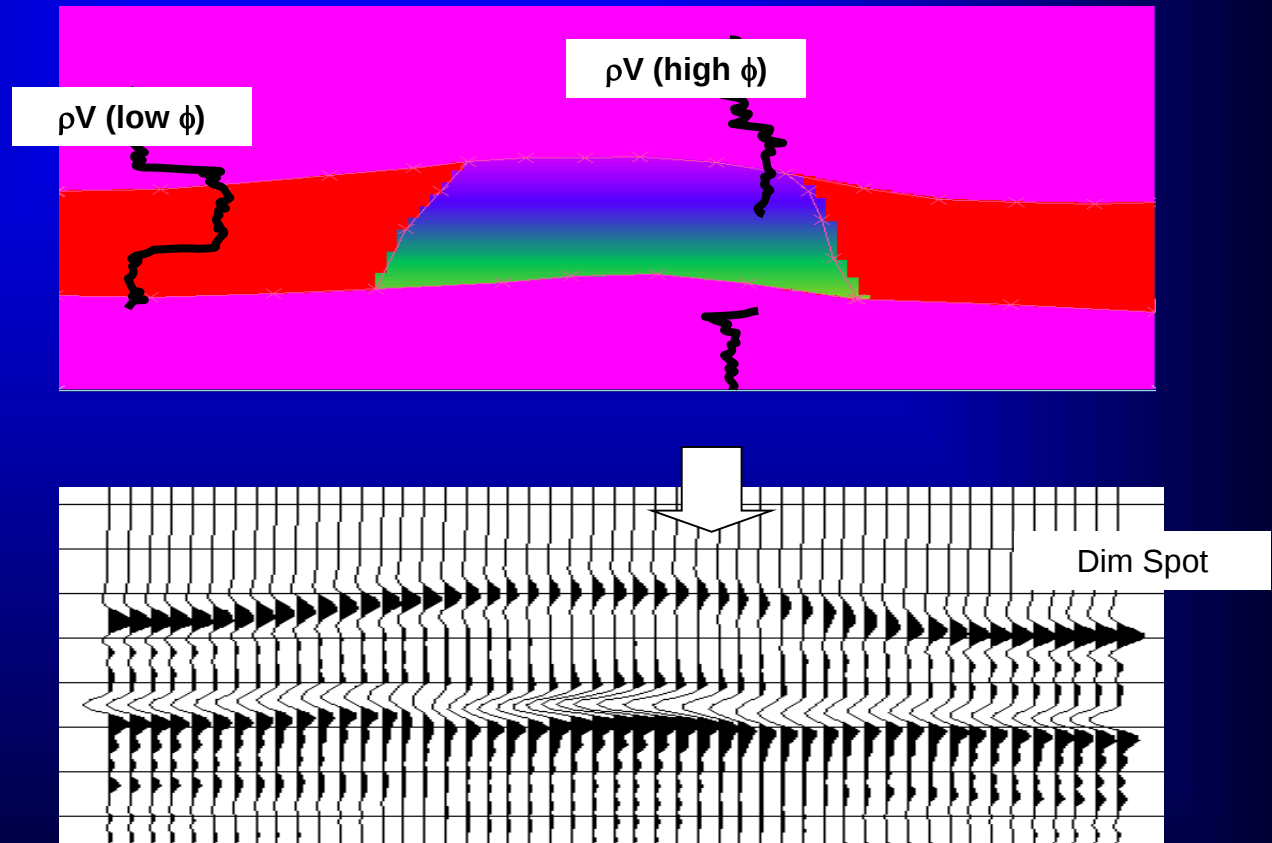


Seismic Attributes

Amplitude-Dim Spot

Frequently, an increase in porosity, $\Delta\phi > 0$, perhaps accompanied by a pore fluid change to hydrocarbons, leads to a decrease in the impedance of an otherwise high impedance rock – such as a carbonate or older SS.

Note the high amplitude exit event - with a time sag caused by the lower velocity in the porous zone





Seismic Attributes

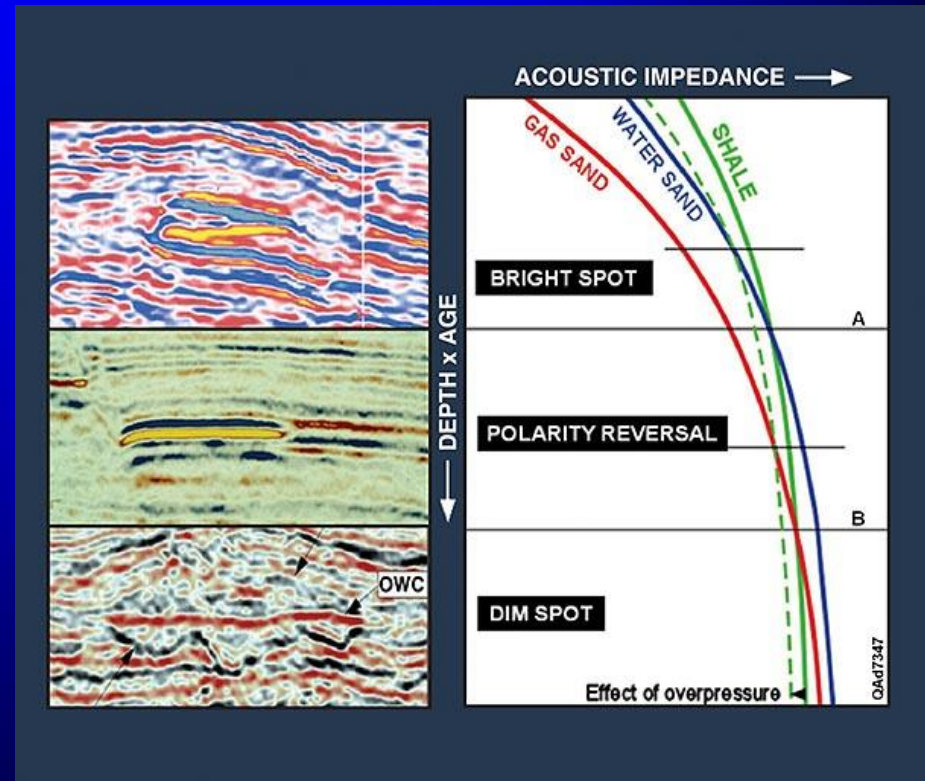
Amplitude-Dim Spot

Generalized curves showing how the acoustic impedances of gas sand, water sand and shales increase with depth.

Bright spot occurs above depth A, where is large contrast in and gas-sand impedances but a modest difference between shale and water –sand impedances.

Polarity reversals occur between depths A and B, where water –sand impedance is greater than shale impedance but gas-sand impedance is less than shale impedance.

Dim spot occur below depth B, where the three impedance curves converge and there are only small impedance contrasts between shale and either type of sand, brine-filled or gas –filled.



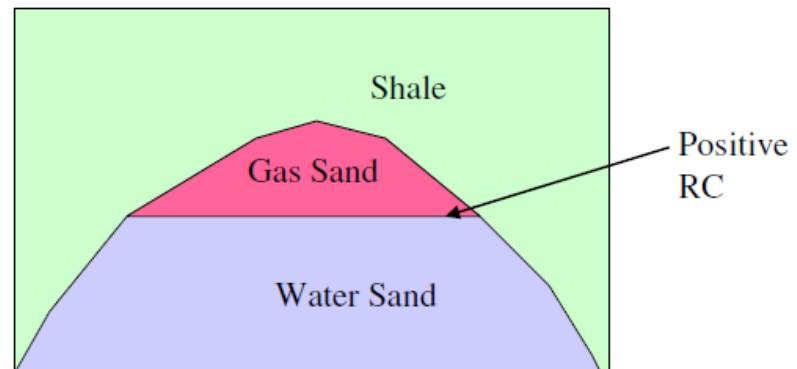
Seismic Stratigraphy

Flat Spots

Estimation of lithology
Estimation of porosity
Fluid content

Flat Spots

- Due to a fluid contact (gas/water, gas/oil, oil/water)

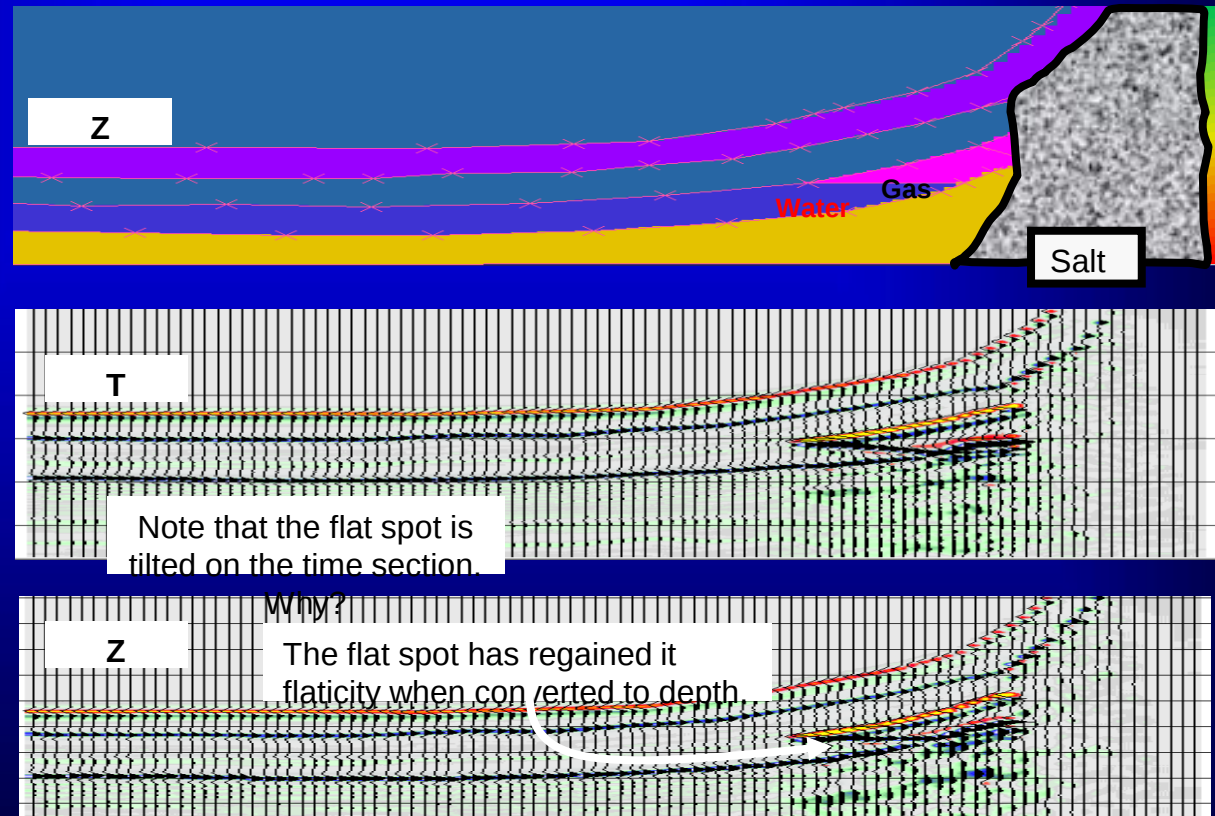


II-15

Seismic Attributes

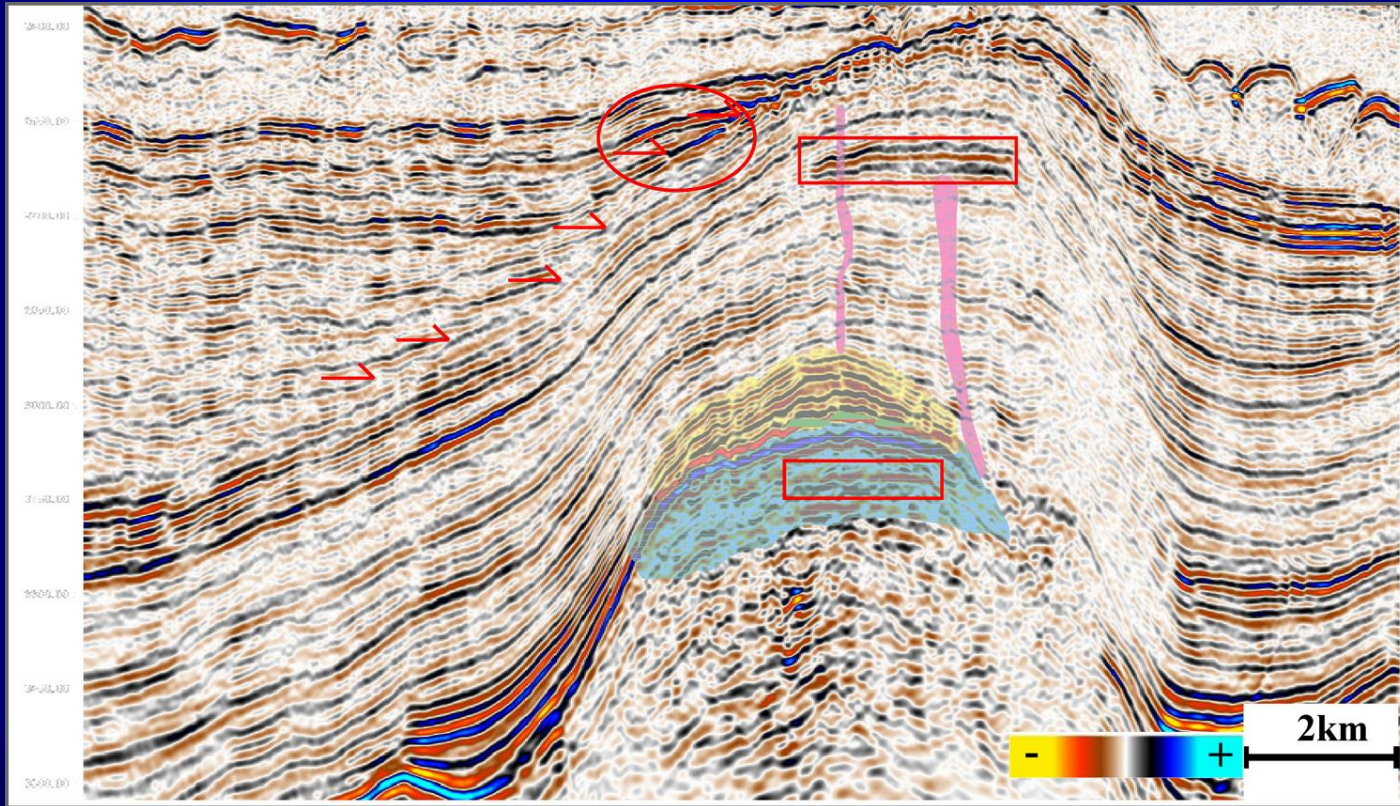
Amplitude-Flat Spot

Old and venerable, the flat spot, resulting from gas-water contact reflections, is still widely used in exploration and development.



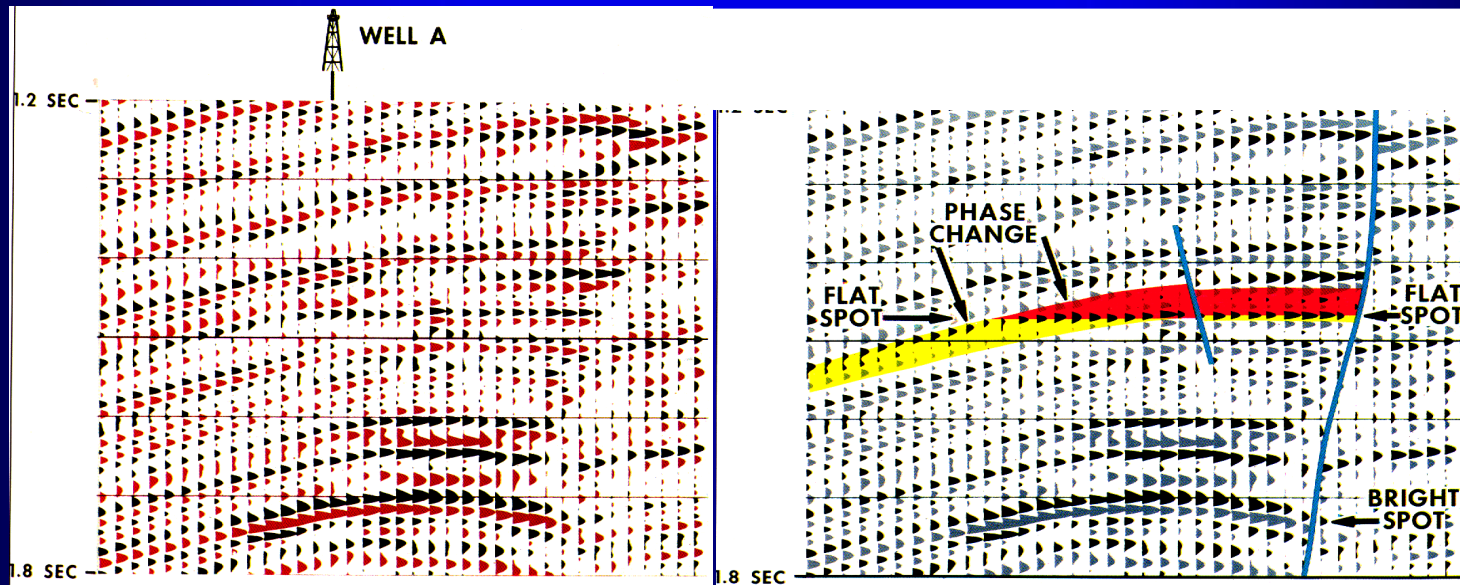
Seismic Attributes

Amplitude-Flat Spot



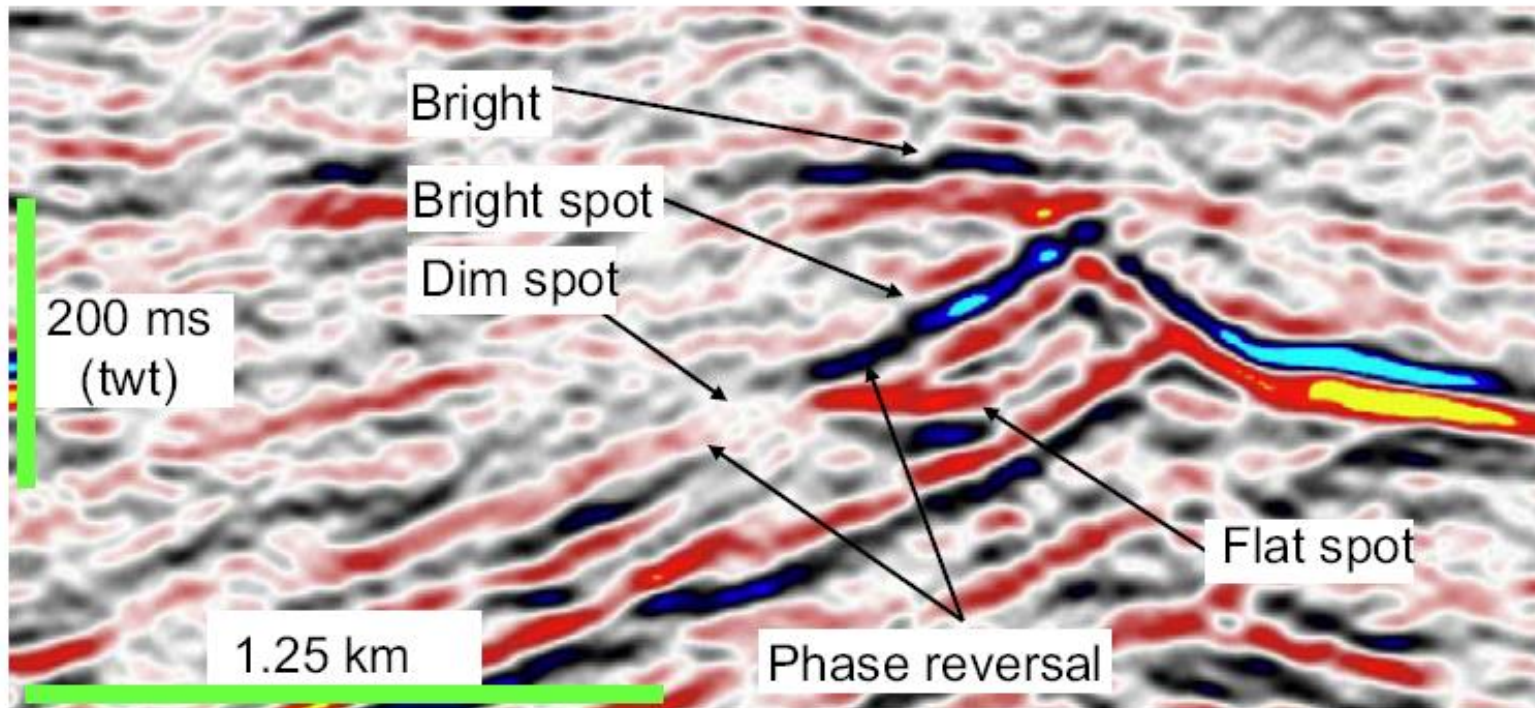
3-Seismic Attributes

Amplitude-Flat Spot



Modified from Brown, 1996

3-Seismic Attributes

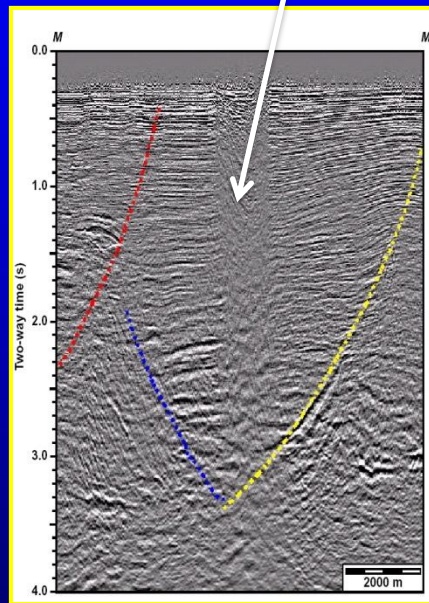
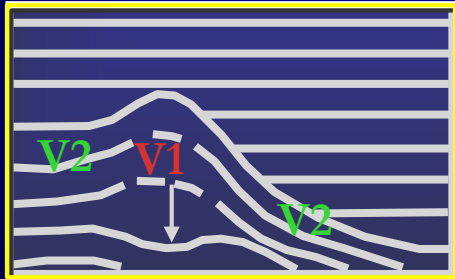
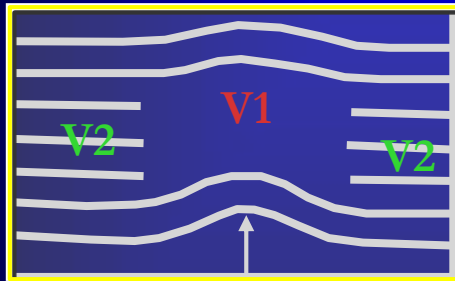


Bright spot, dim spot and flat spot suggest the presence of hydrocarbon in a reservoir. Note also the increased amplitude and continuity in the cap rock just above the hydrocarbon-filled reservoir.

Velocity Impact

Interval velocity:

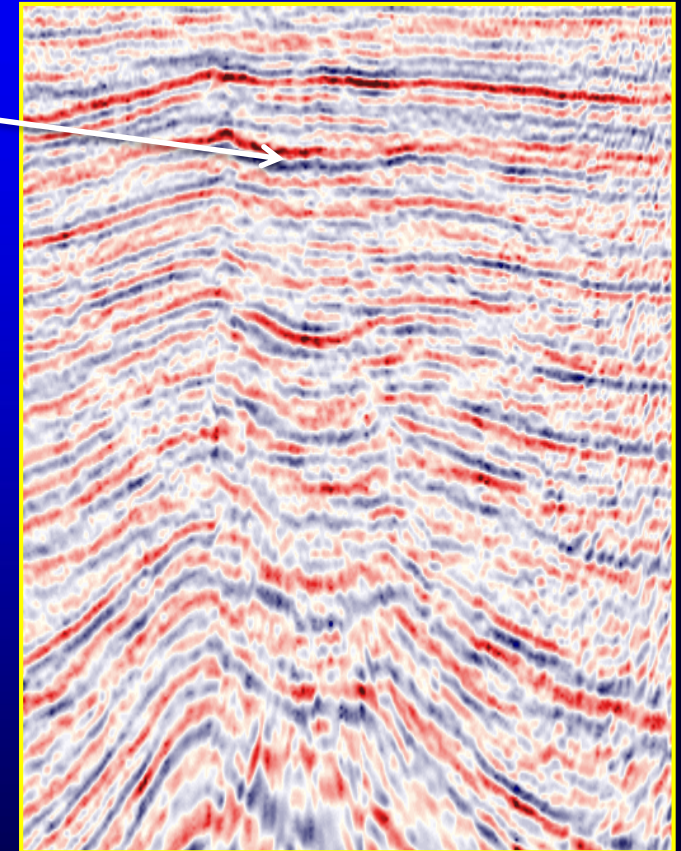
Estimation of lithology
Estimation of porosity
Fluid content



Velocity Anomaly - pull down

$$V1 < V2$$

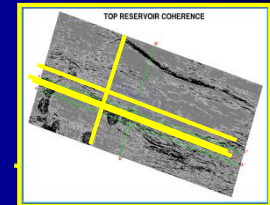
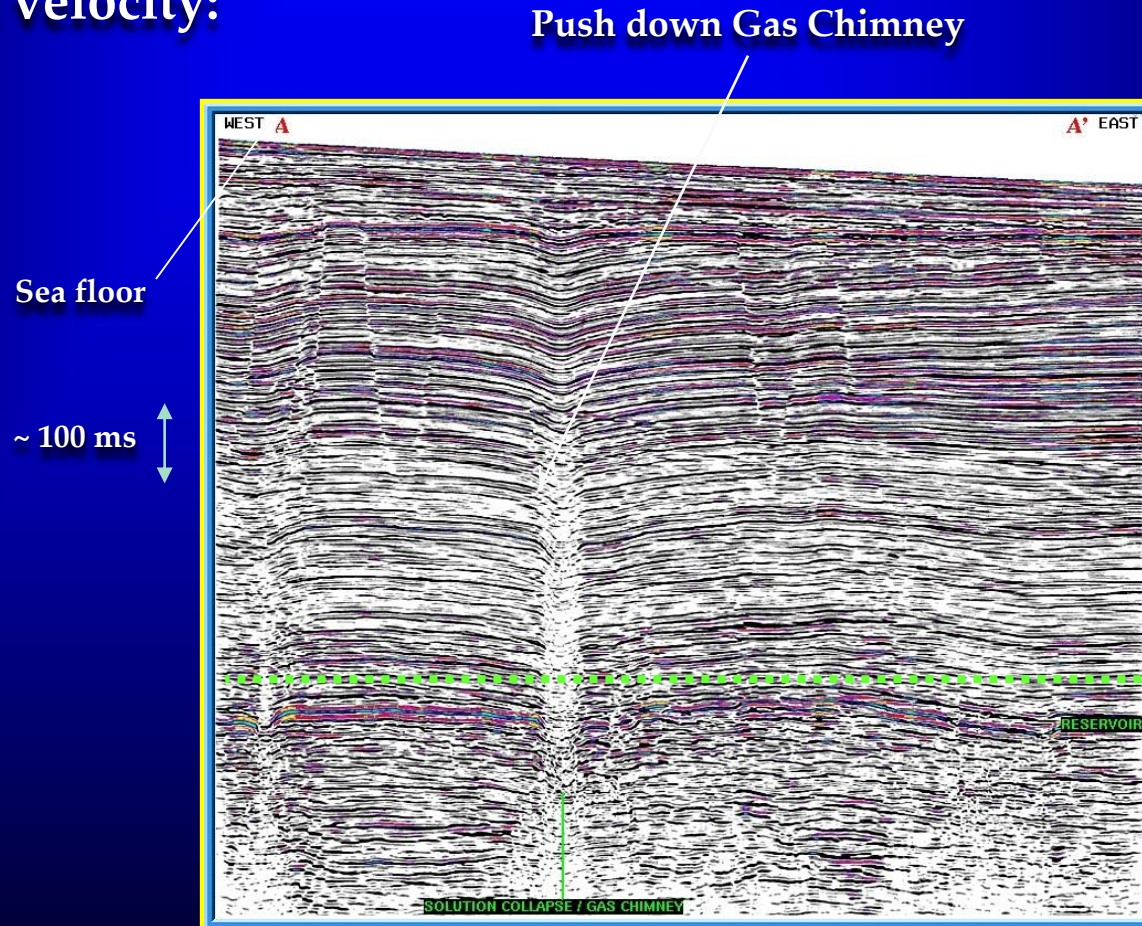
$$\text{Velocity: } V = (\rho/c)^4$$



Push down (velocity sag) due to gas accumulation

Velocity Impact

Interval velocity:



Plio-
Pleistocene
turbidities

Top Reservoir
(= Top A)

ALI BAKR

Gas chimney emanating from sinkhole;
amplitude reduction and structural / gas s...

Velocity Impact

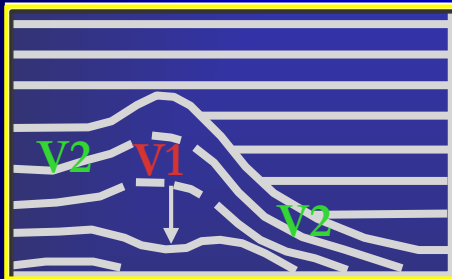
Interval velocity:

Estimation of lithology

Estimation of porosity

Fluid content

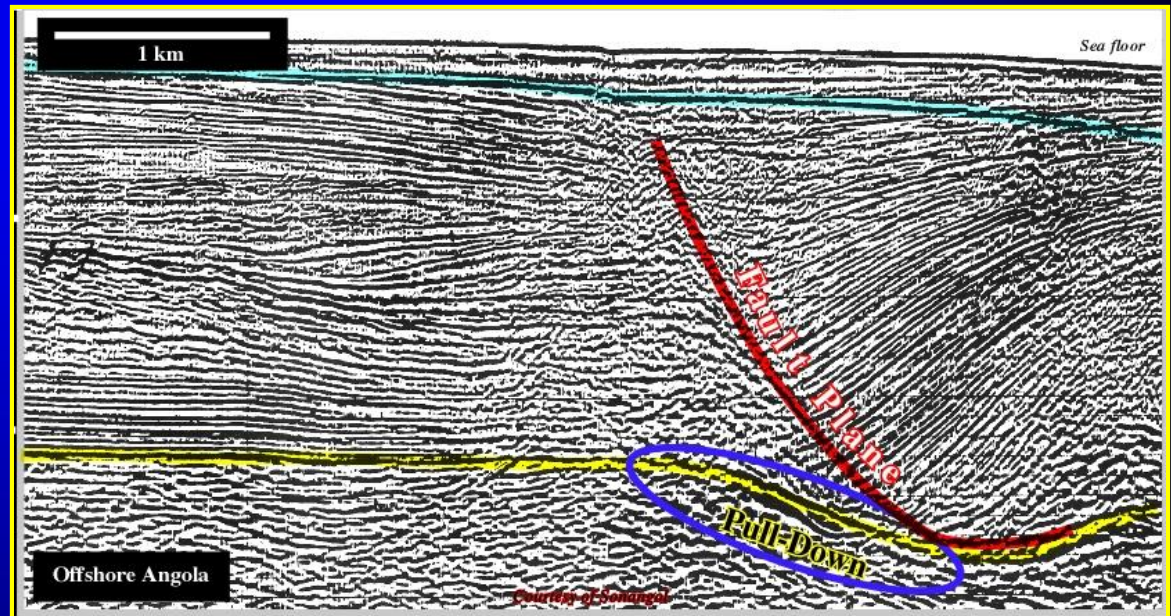
Pull up & Pull down



Velocity Anomaly - pull down

$$V1 < V2$$

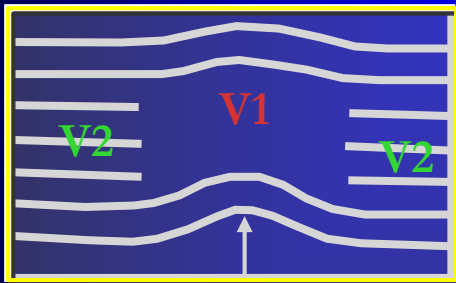
$$\text{Velocity: } V = (\rho/c)^4$$



On this seismic line from offshore Angola, the pull-down of the yellow marker (bottom of the evaporitic interval) is induced by the lateral change of the interval-velocity created by the normal fault which limits a Upper Tertiary depocenter. Indeed, such a fault put limestones (upthrown block) and shales (downthrown block in juxtaposition).

Velocity Impact

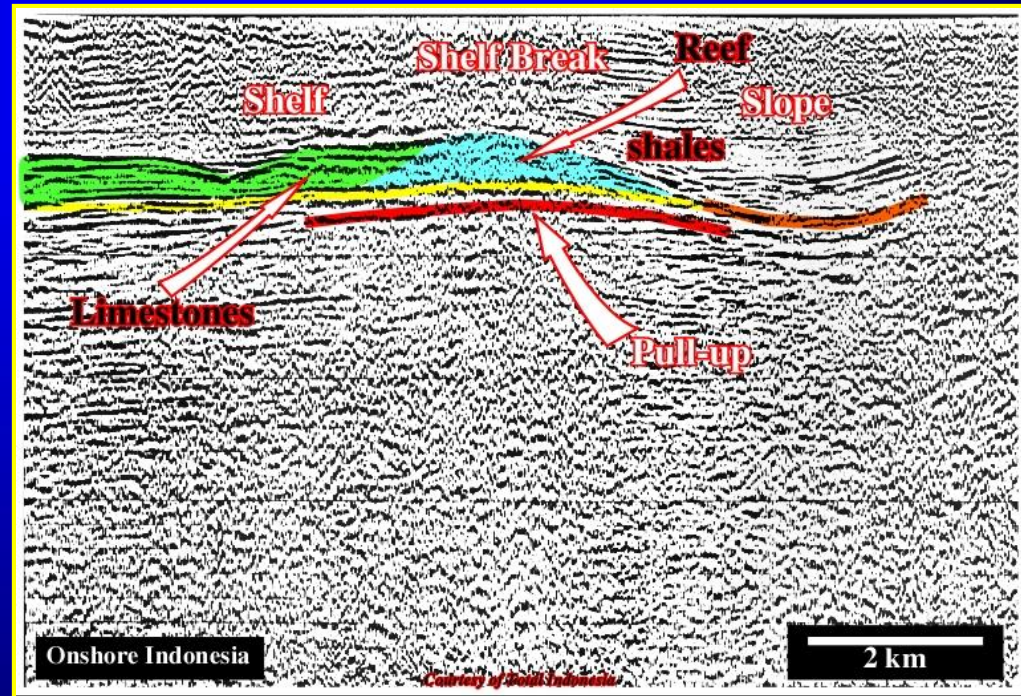
5- Interval velocity:



Velocity Anomaly - pull up

$$V1 < V2$$

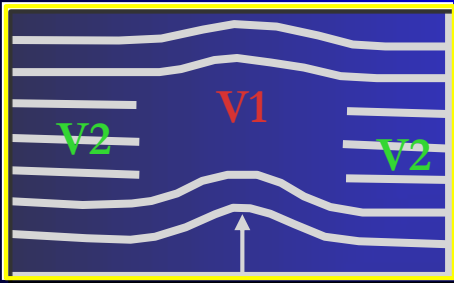
$$\text{Velocity: } V = (\rho/c)^4$$



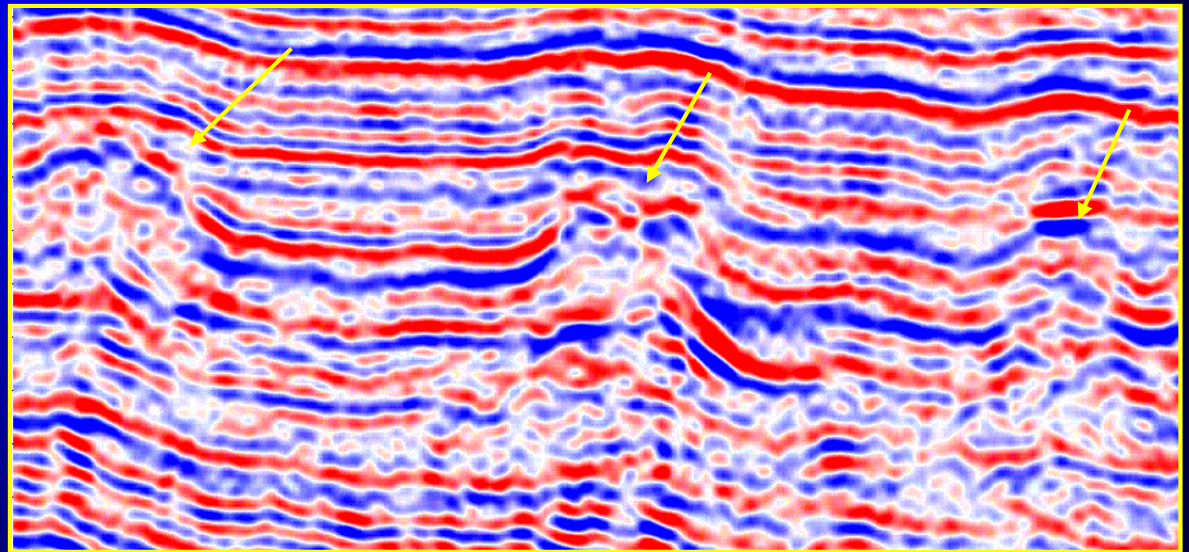
On this reef geological model, above a planar limestone sole (light blue), a reef with a compression wave velocity of 5490 m/s, is laterally bounded by shaly sediments (yellow) with a much lower velocity (3660 m/s), which are overlain by even slower sediments (brown interval, 3050 m/s). The seismic answer of such a model is roughly depicted on the right. The horizon associated with the bottom of the reef shows a significant pull-up.

Velocity Impact

5- Interval velocity:

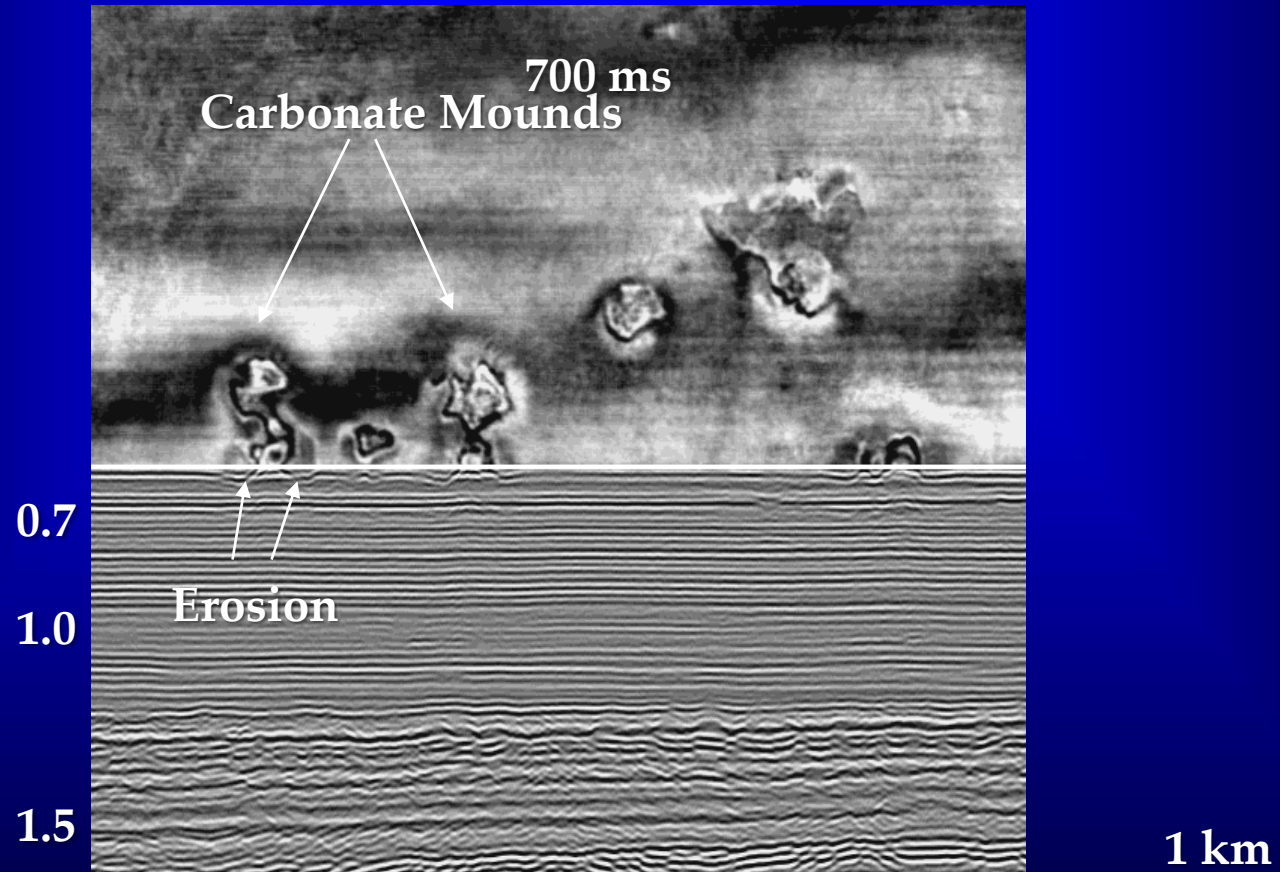


Velocity Anomaly - pull up



Palaeozoic carbonate reef build-ups (Barents Sea)

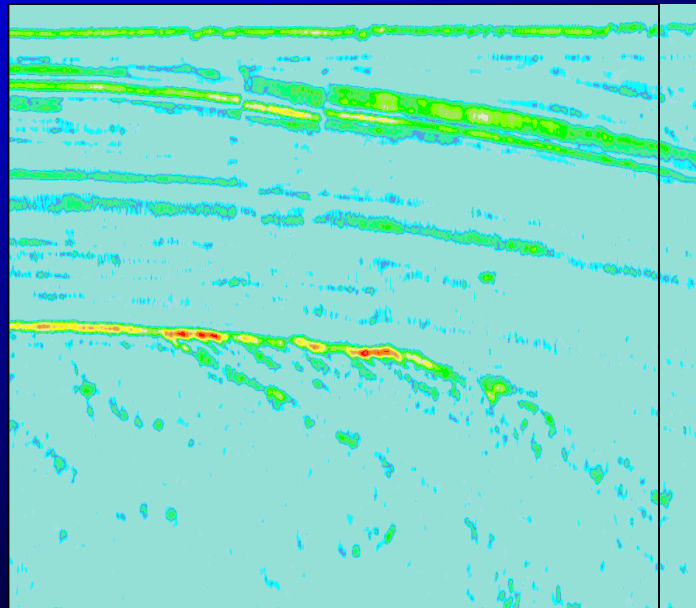
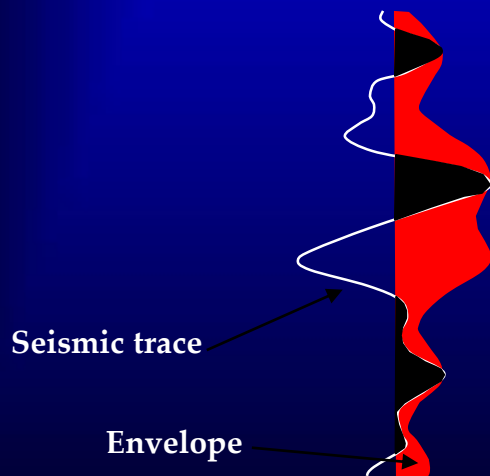
Velocity Impact



3D Seismic, Composite Display, Danish North Sea

Display and use of Seismic Attributes

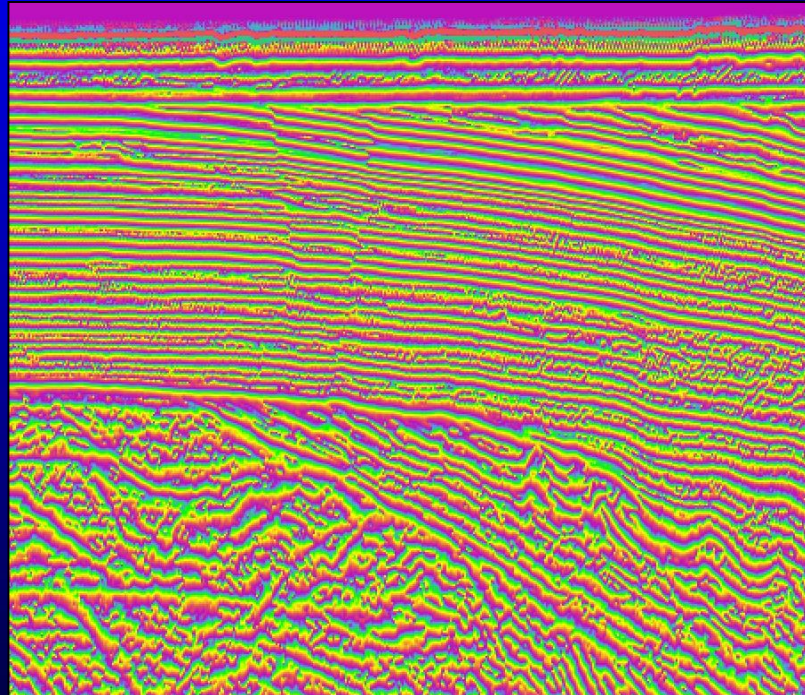
- **Reflection Strength/Envelope:**
 - Total envelope of energy at any instant along the trace
 - High reflection strength is often associated with major change in acoustic impedance due to lithology, fluid content (gas), or stratigraphy.



Display and use of Seismic Attributes

- **Instantaneous Phase**
 - Description of the phase angle at any instant along a trace
 - Independent of amplitude

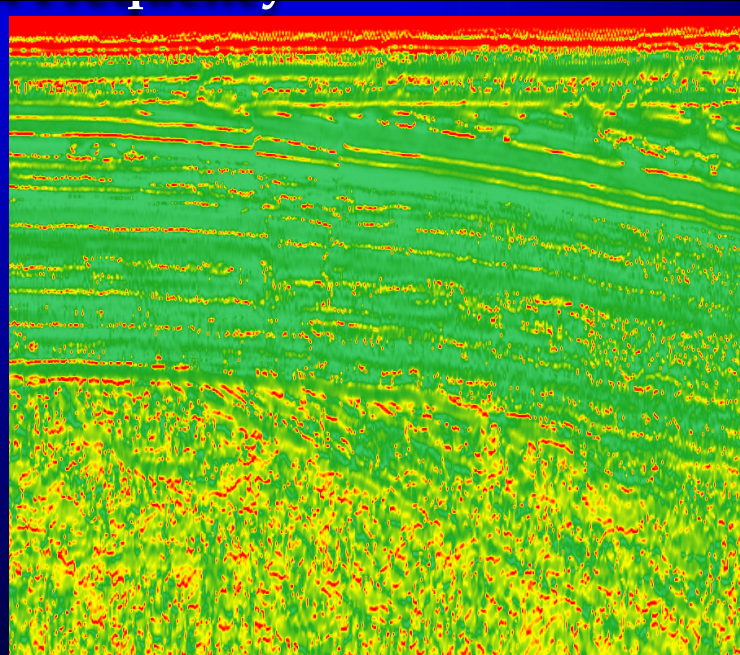
Expresses the degree of lateral continuity or discontinuity of seismic reflections, pinchouts, angular unconformities, thickening and thinning zones, offlap, onlap, and makes weak coherent reflection clearer.



Display and use of Seismic Attributes

- **Instantaneous Frequency:**
 - Time derivative of the phase
 - Low: 0 to 1/2 of the Nyquist Frequency

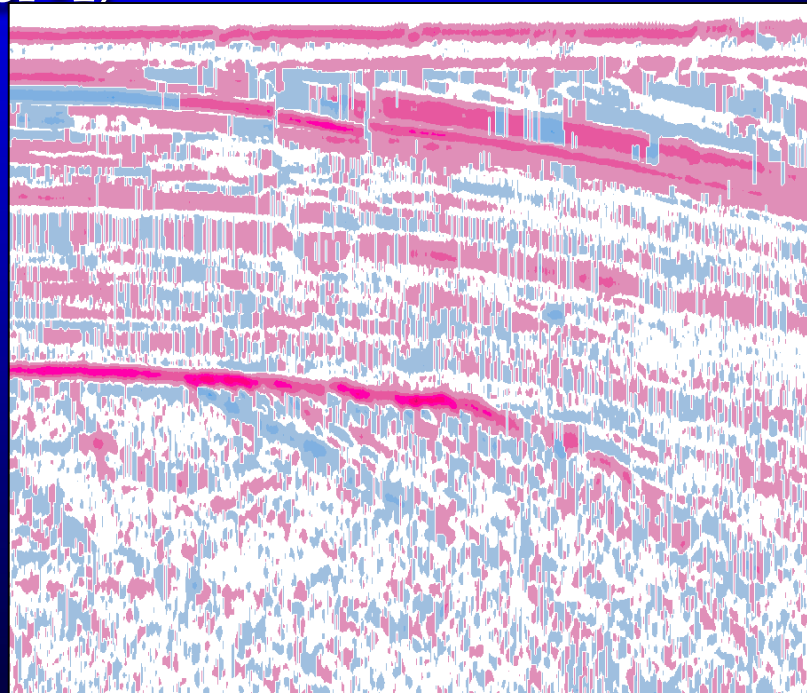
Helps in correlating reflection along seismic section and highlights low frequency anomalies below HC accumulations



Display and use of Seismic Attributes

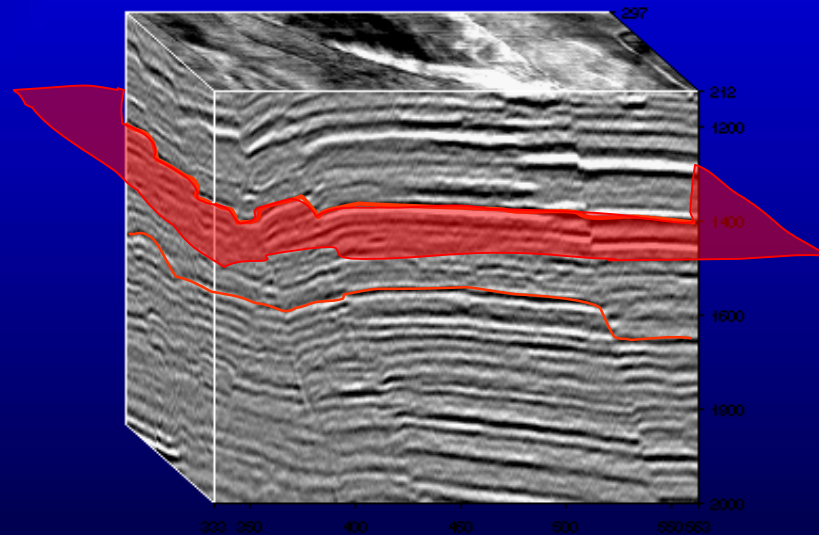
- Apparent Polarity:
 - Sign of the seismic trace where reflection strength has a local maximum value (+1 or -1)

May help distinguish different kinds of bright spots (due to gas, limestone..)



Display and use of Seismic Attributes

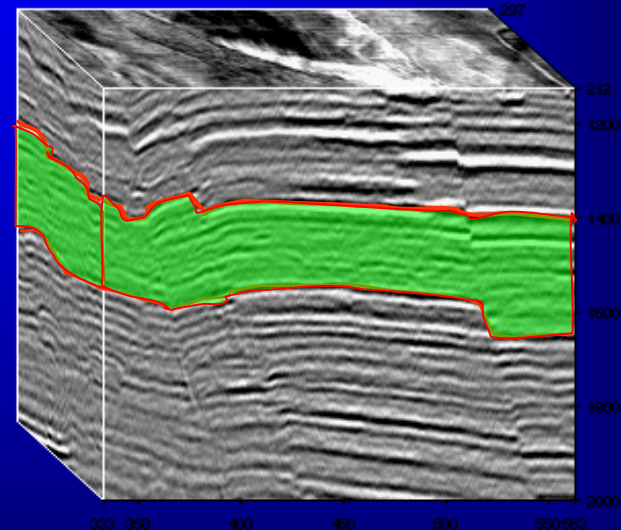
- Surface based attribute maps:
 - Extracted along or close to an interpreted surface



Extracted along or
close to a surface

Display and use of Seismic Attributes

- Volume based attribute maps:
 - Calculated in a time/depth window:
 - Between two interpreted surfaces
 - Below/above/around an interpreted surface

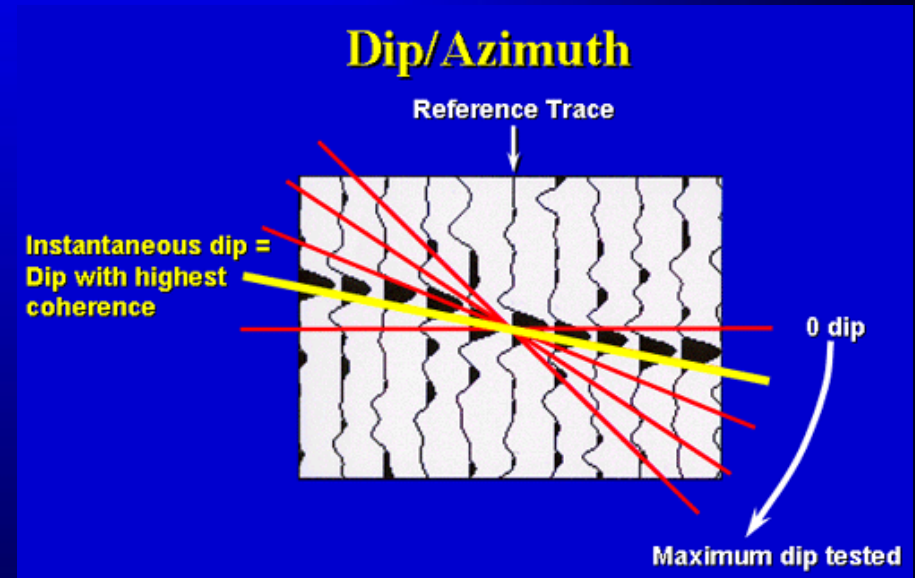
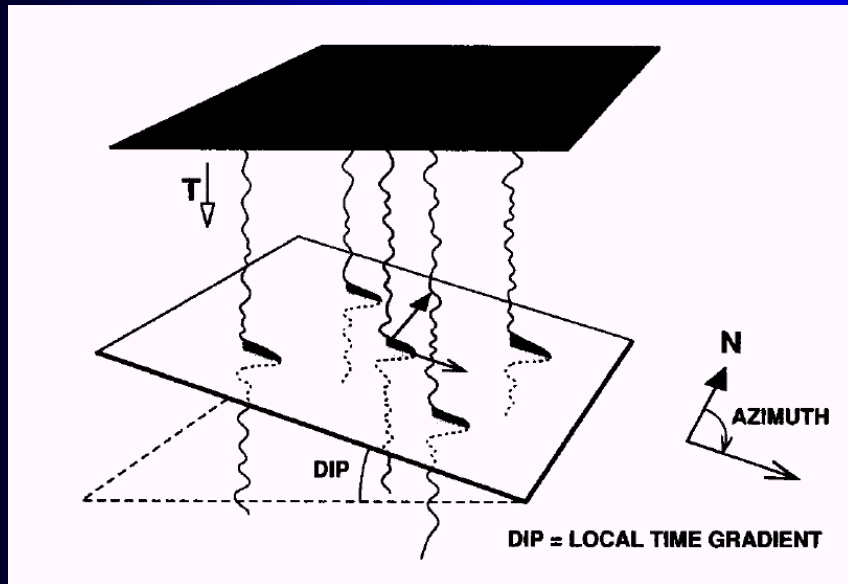


Extracted in between two surfaces or within a constant time window

Seismic Geometrical Attributes

Horizon Attributes Dip & Azimuth

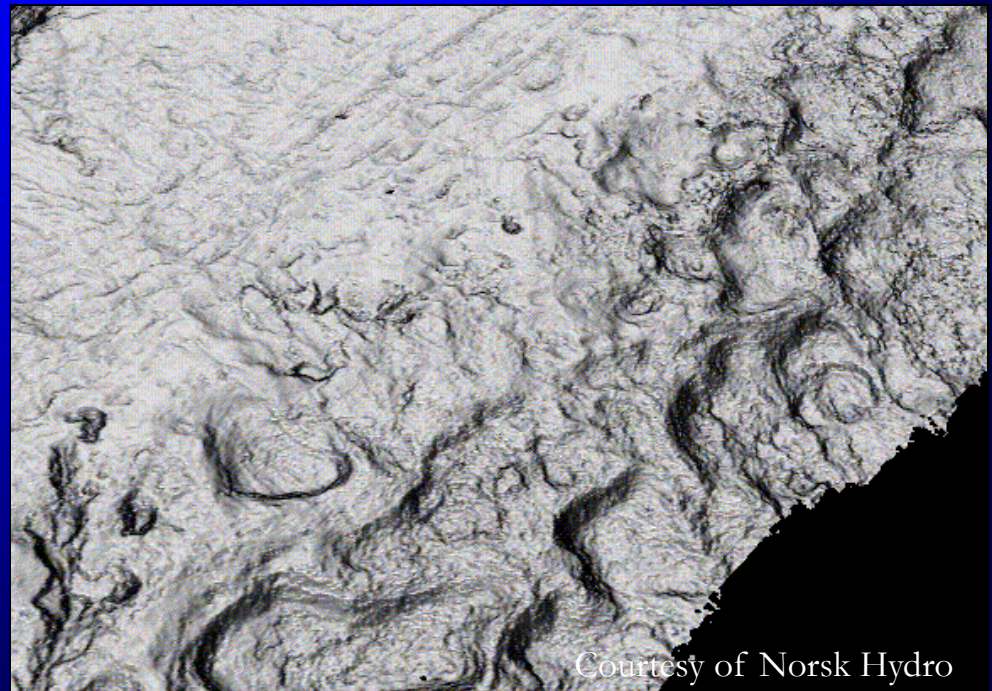
3-D dip/azimuth is the dip and azimuth of the most coherent reflector within the analysis window



Numerical estimation of the instantaneous dip and azimuth of reflectors within a seismic volume

Display and use of Seismic Attributes

- Grid based attribute maps:
 - Derived directly from seismic interpretation, independent of seismic amplitude data
 - Dip, Azimuth, Curvature, Illumination, Edge, etc...

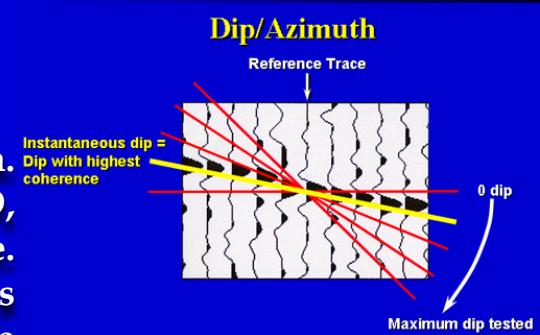


Dip map Carbonate Buildups, Barents Sea

Seismic Attributes Summery

Horizon Attributes Dip & Azimuth

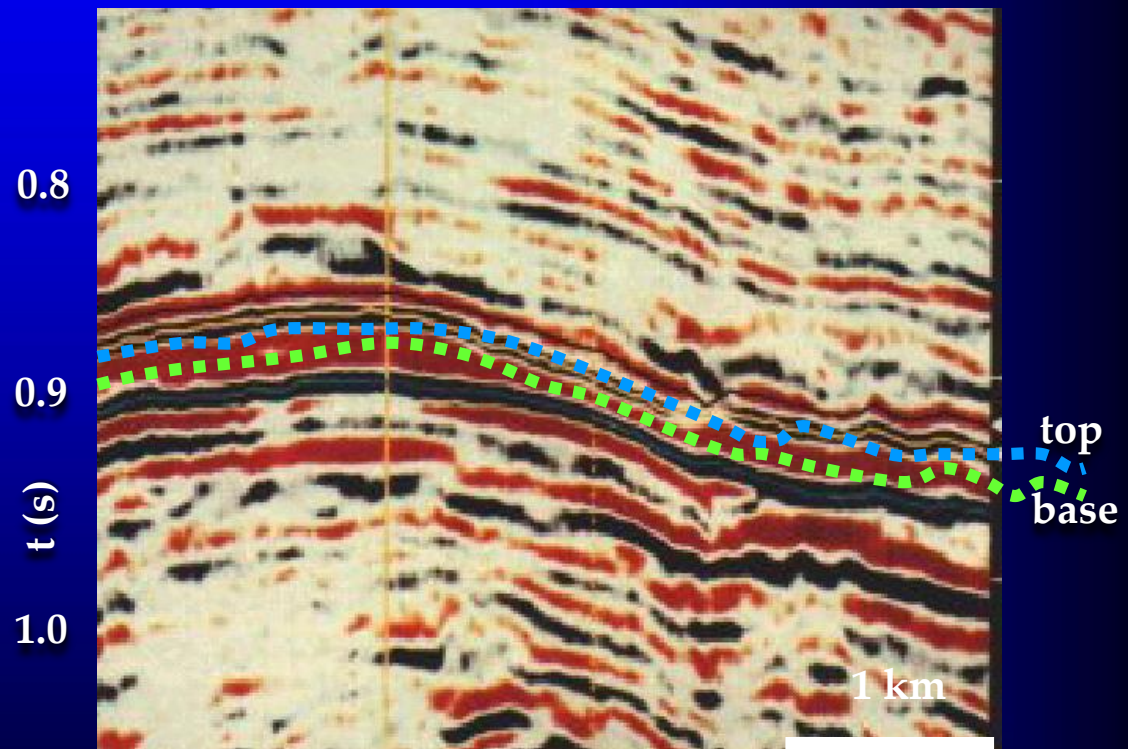
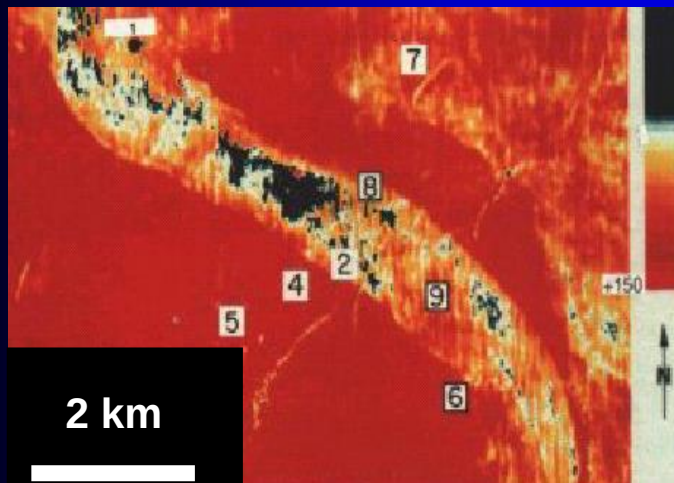
- A schematic 2-D representation of the dip/azimuth calculation. Coherence is calculated for a range of dips (red lines), and in 3-D, azimuths, within a small analysis window around a reference trace. The dip/azimuth combination which has the highest coherence is assigned to be the instantaneous dip/azimuth for the point at the center of the analysis window.
- Dip/azimuth cubes only show *relative* changes in dip and azimuth, since we do not in general have an accurate time to depth conversion
- Dip/azimuth estimated using a vertical window in general provide more robust estimates than those based on picked horizons
- Dip/azimuth volumes form the basis for volumetric curvature, coherence, and structurally-oriented filtering
- Dip/azimuth will be one of the key components for future computer-aided 3-D seismic stratigraphy



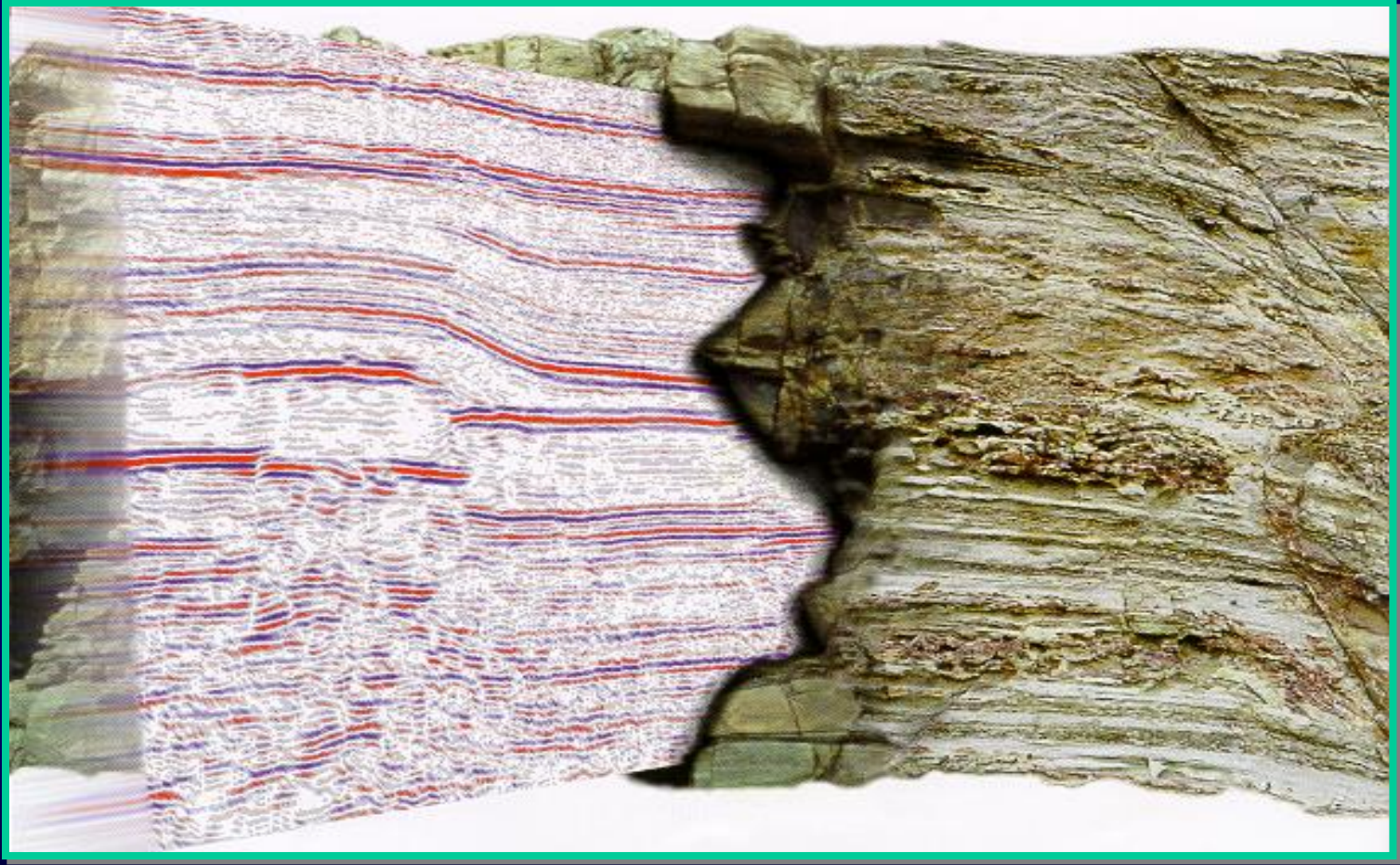
Seismic Attributes

Horizon Attributes Horizon Amplitude Extraction

(Rijks and Jauffred, 1991)



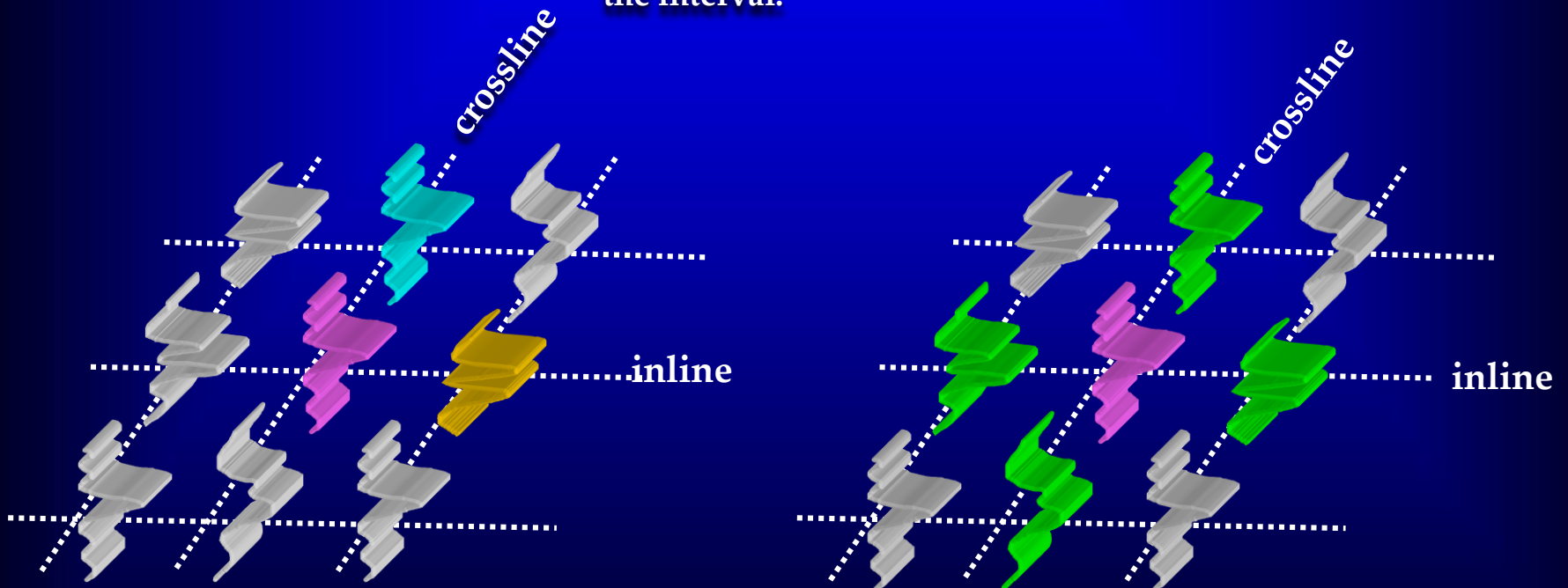
Geometric Attributes Looking for Similarity



Seismic Attributes

Coherency Attribute

- Coherence averages over a window and looks for similarities and then infers dissimilarity.
- Coherence used trace to trace cross correlation and averages the interval.



Coherence compares the waveforms of neighboring traces

Seismic Attributes

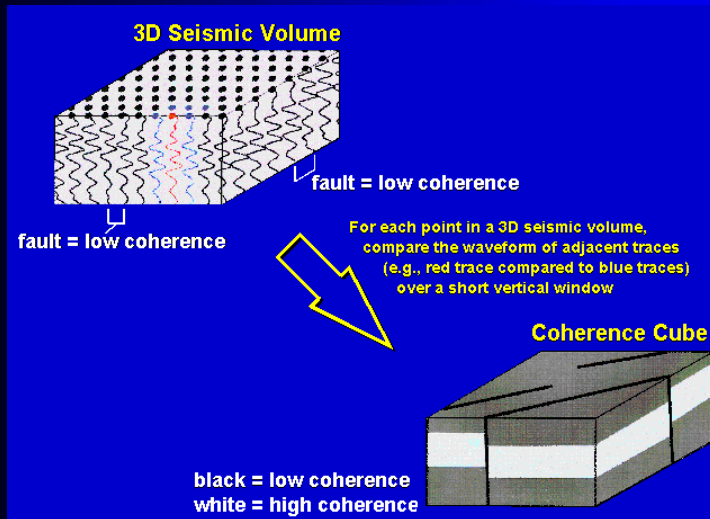
Coherency Attribute

Why we use Coherency

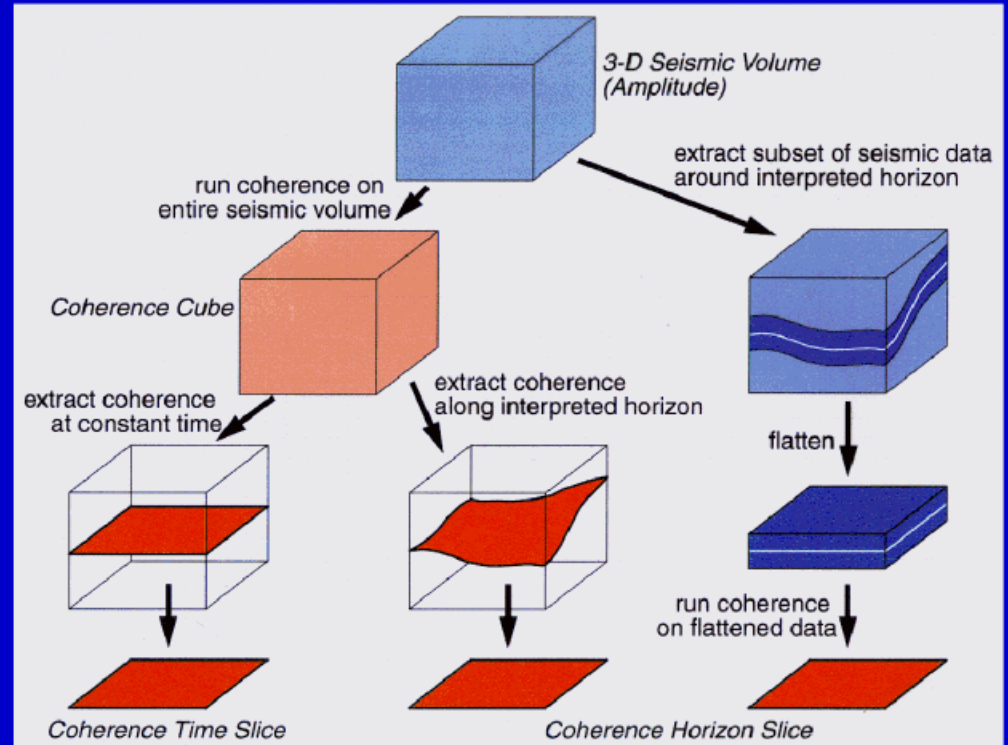
- Excellent tool for delineating geological boundaries (faults, lateral stratigraphic contacts, etc).
- Allows accelerated evaluation of large data sets.
- Provided quantitative estimate of fault /fracture presence.
- Often enhance stratigraphic information

Seismic Attributes

Coherency Attribute Coherency data volume



Methods for obtaining a coherence slice from a 3-D seismic volume



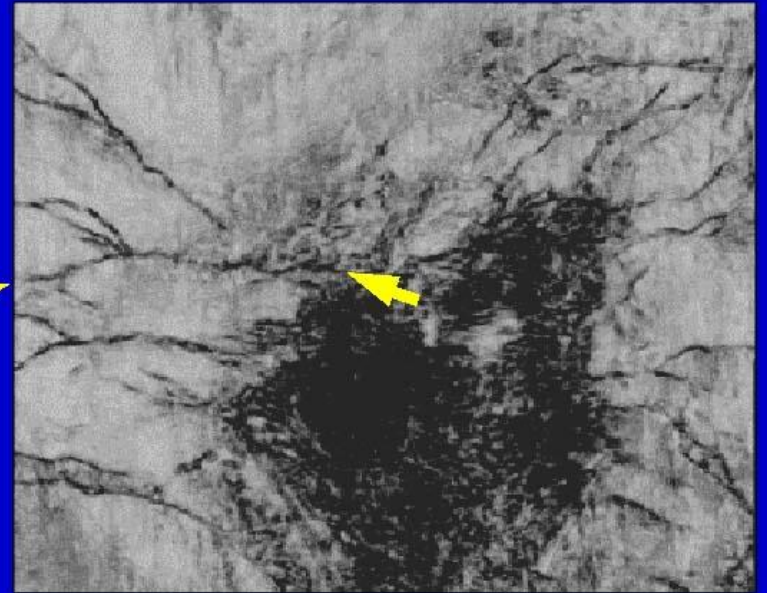
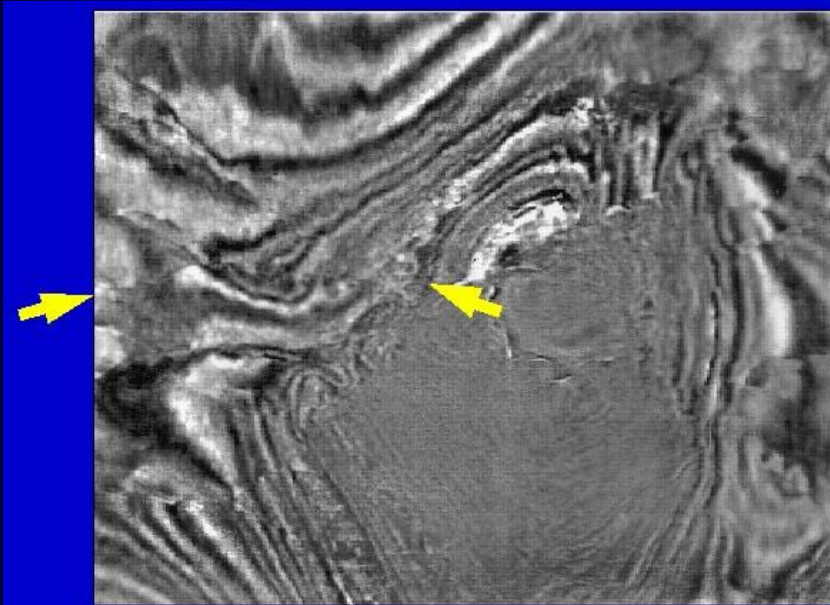
Measure of the trace-to-trace similarity of the seismic waveform within a small analysis window

Seismic Attributes

Coherency Attributes

Coherency data volume

Seismic Time Slice

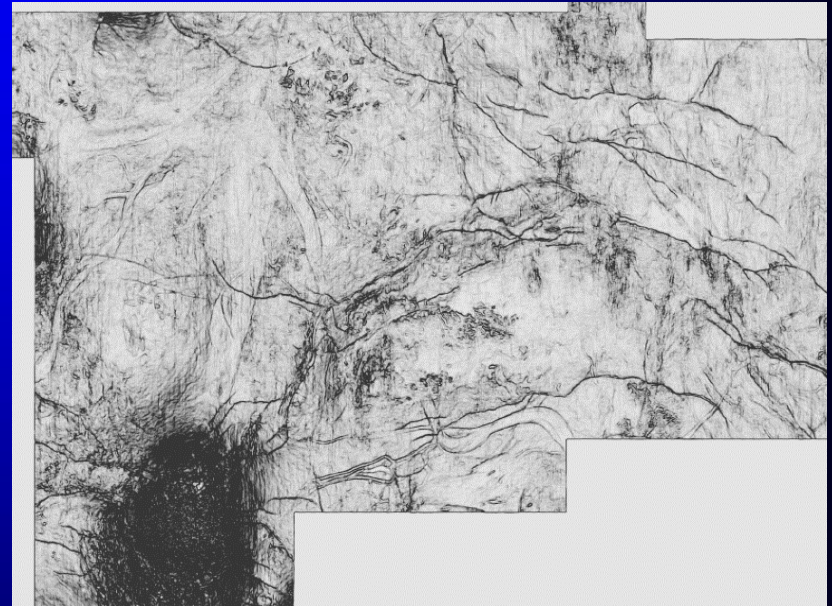
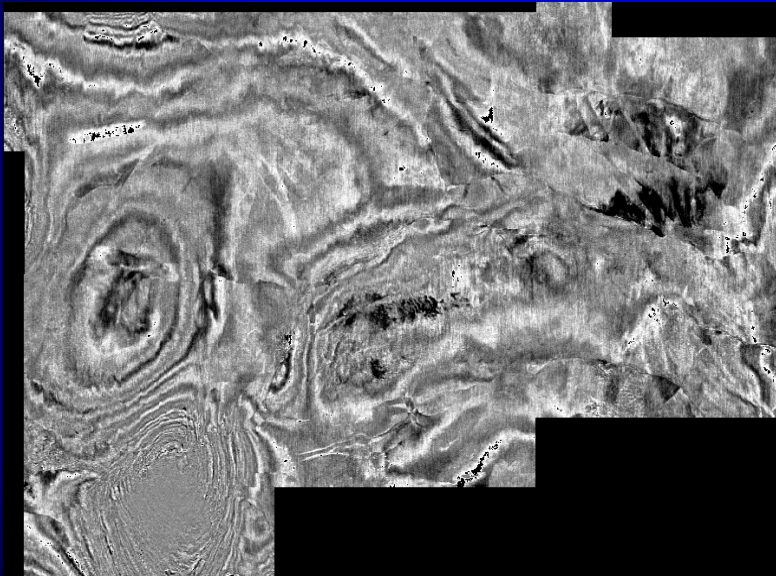


Coherence Time Slice

Seismic Attributes

Coherency Attribute **Coherency data volume**

Seismic Time Slice



Coherence Time Slice

Ant Tracking Biology lesson



Nest

Food

Ant Tracking

Biology lesson: swarm intelligence

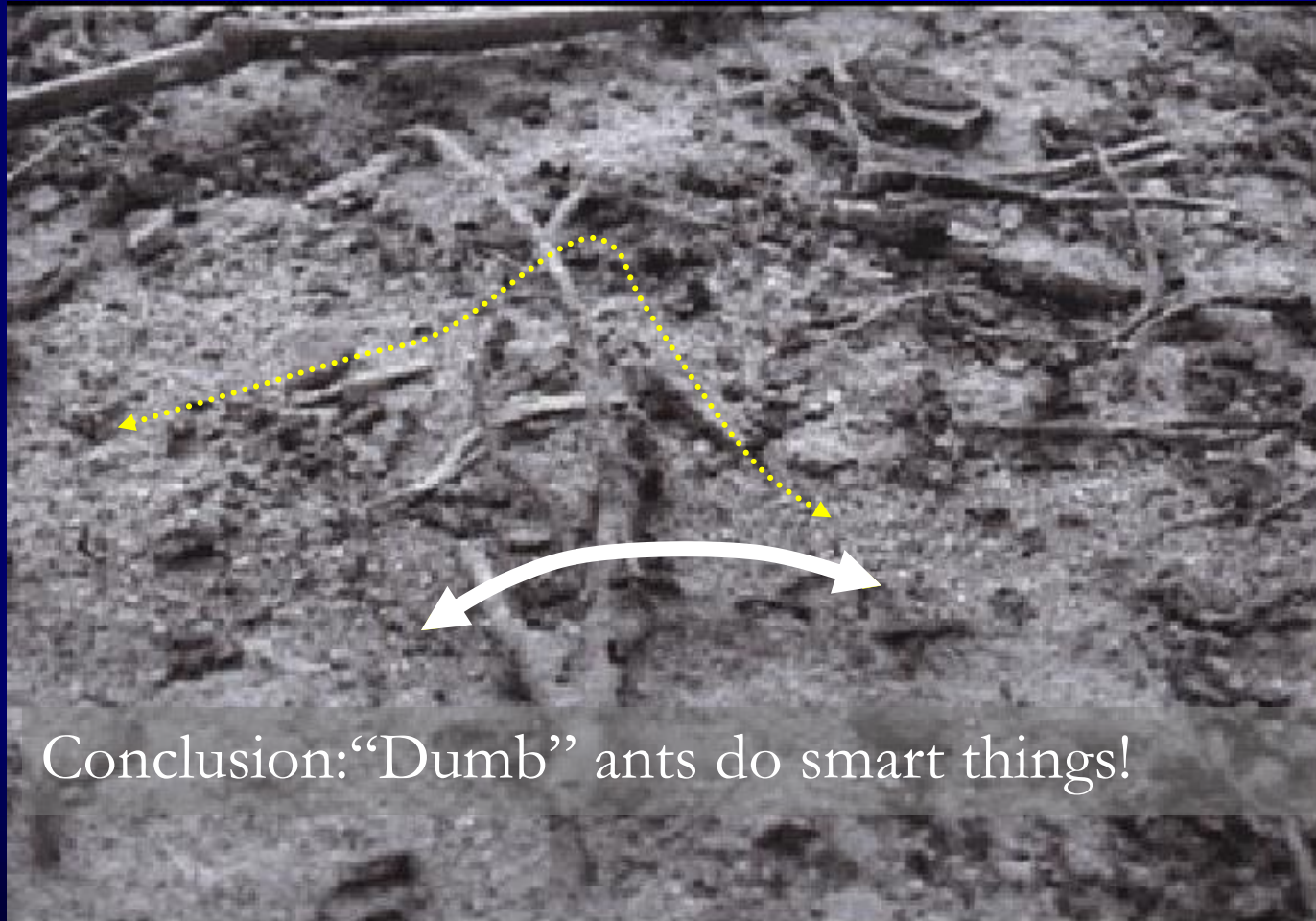


Nest

Food

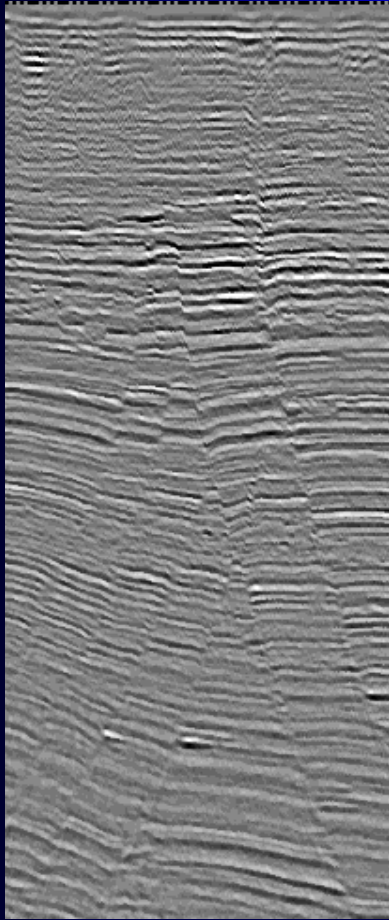
Ant Tracking

Biology lesson: swarm intelligence

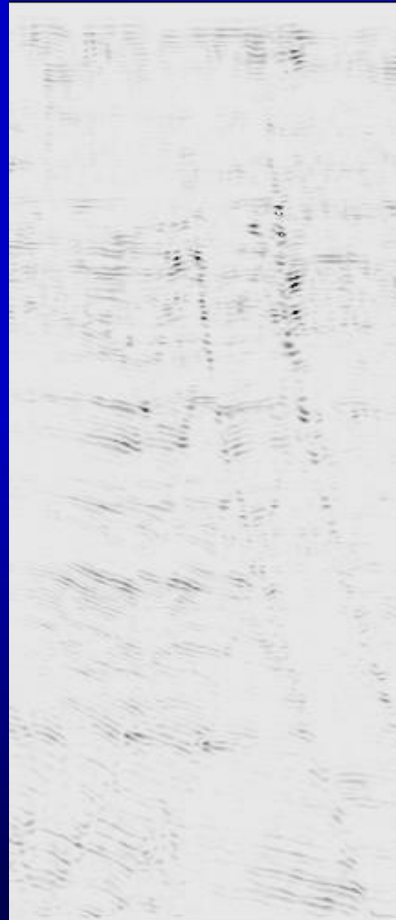


3D Automated Fault Mapping

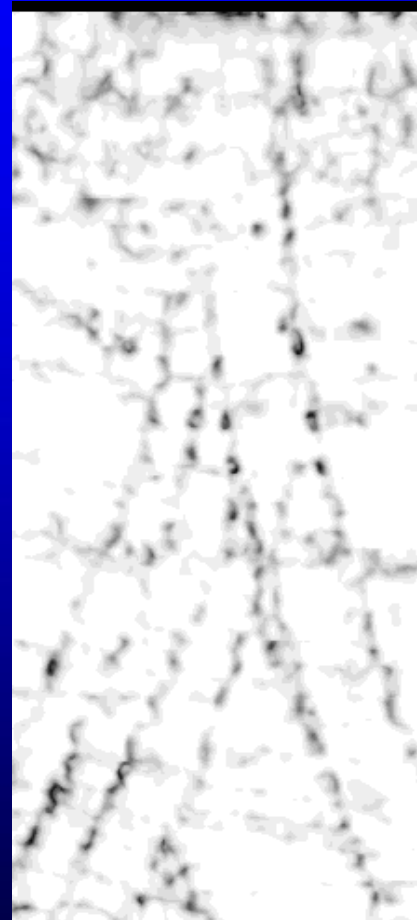
Ant Tracking: Results



Seismic



Variance

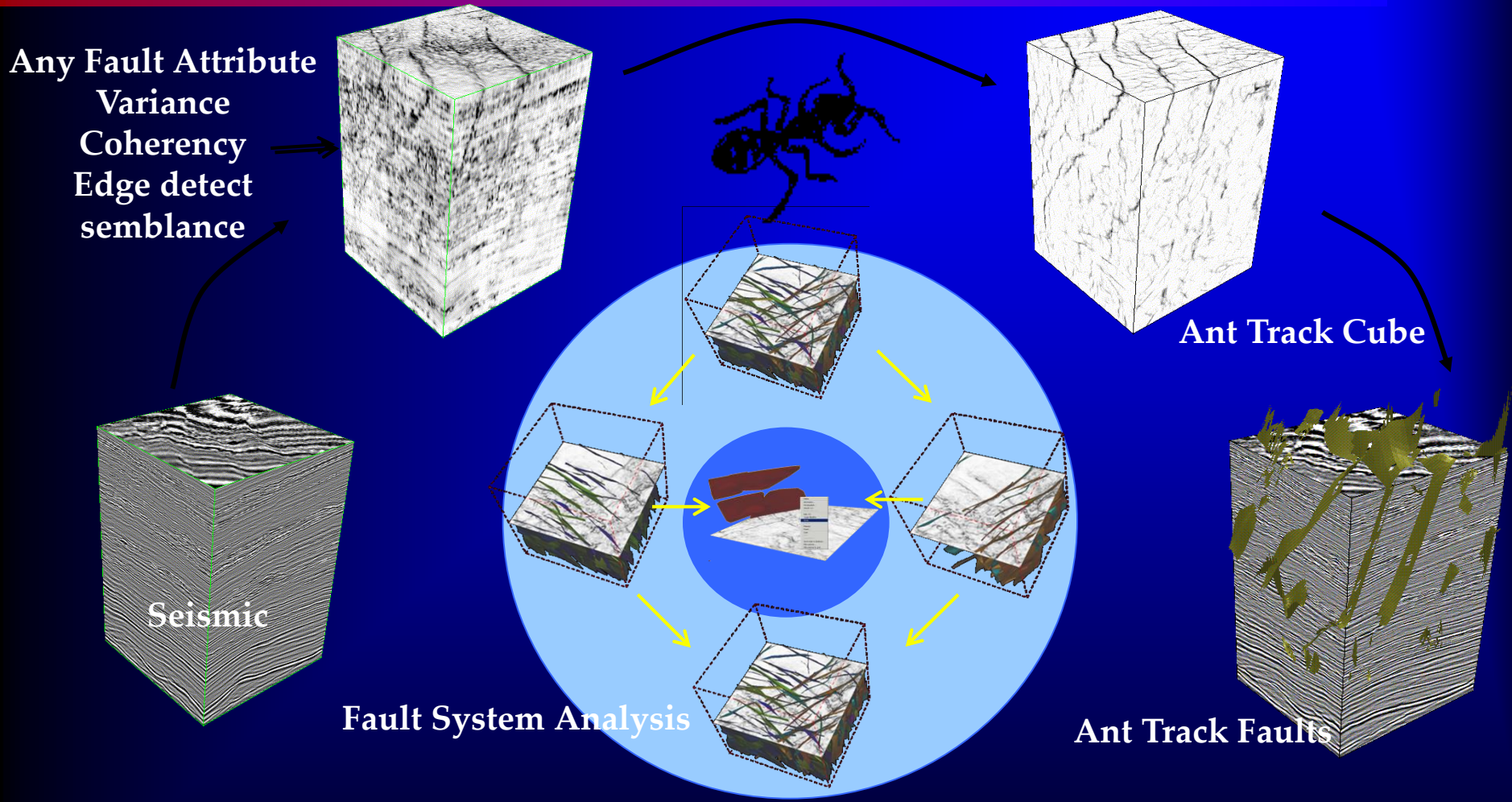


Chaos



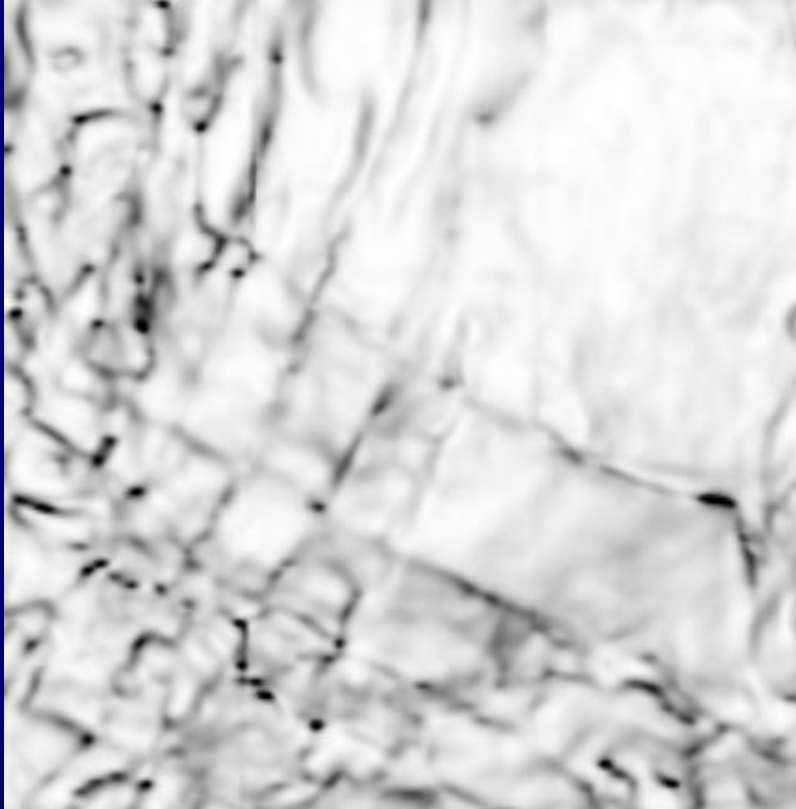
Ant track

Automated Fault Mapping Ant Tracking

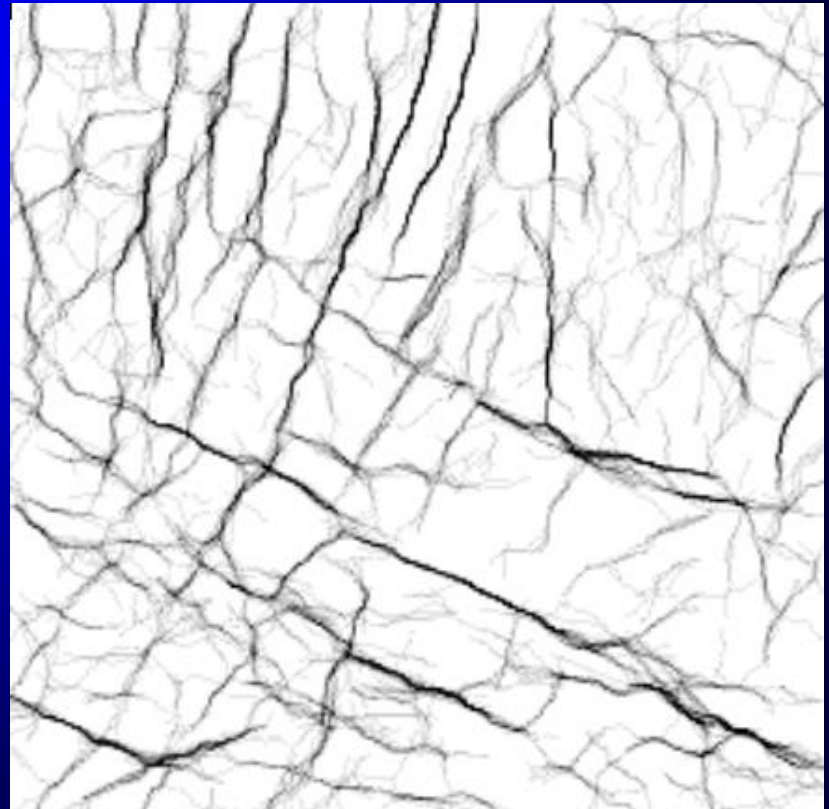


Fault Attribute vs. Ant Tracking

Time slice



Variance



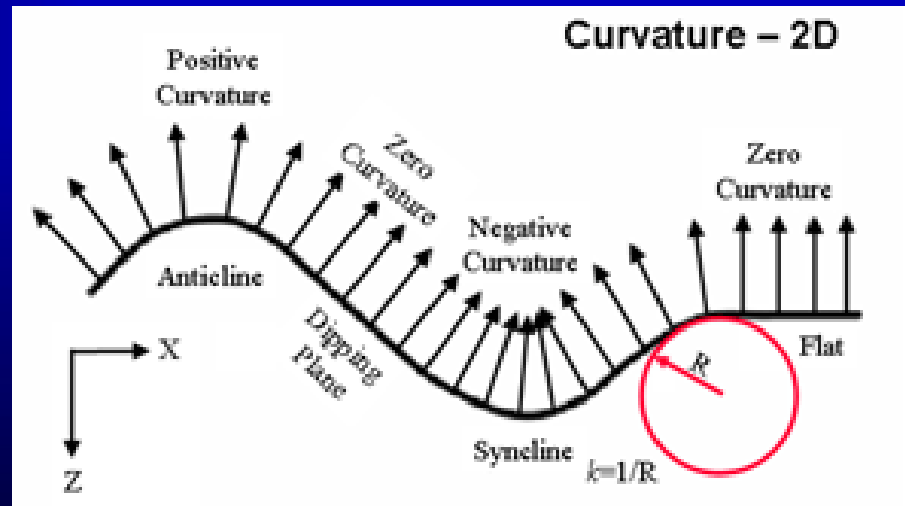
Ant track

Geometrical Attributes

Curvature

Curvature describes how bent a surface is at a particular point and is closely related to the second derivative of the curve defining the surface. The more bent a surface is, the larger its curvature.

In two dimensions, positive curvature refers to an antiform feature, negative curvature refers to a synform feature, and zero curvature refers to a planar feature.



Geometrical Attributes

Curvature

Maximum Curvature ($k_{\max}$) - measure of the maximum bending (positive or negative) of the surface at a point

Minimum Curvature ($k_{\min}$) - curve perpendicular to the maximum curvature

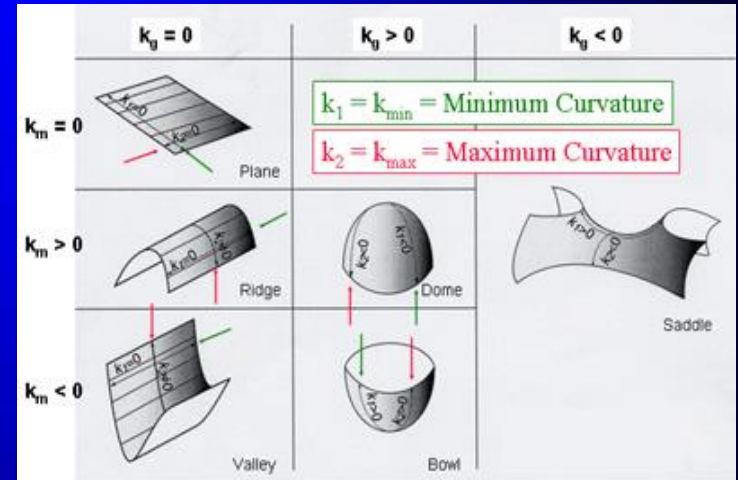
These curvatures can be combined to define other curvature attributes, such as:

Mean Curvature ($k_m = (k_{\max} + k_{\min}) / 2$) - approximates the average curvature through a point

Gaussian Curvature ($k_g = k_{\max} * k_{\min}$) - indicates whether a surface has been warped or not

Curvedness ($r = (k_{\max}^2 + k_{\min}^2)^{1/2}$) - measure of intensity of folding

Shape Index ($s = [(k_{\max} + k_{\min}) / (k_{\max} - k_{\min})]$) - describes local structure as dome, bowl, ridge, plane, etc.



Seismic Attributes

Data specification needed for Attributes

- For 8-bit data, amplitudes theoretically range from ± 128 , 16-bit data theoretically range from $\pm 32,768$ and 32-bit data range from $\pm 4,294,967,296$. 32- and 16-bit data have more dynamic range than 8-bit data, but take up correspondingly more amounts of storage space.
- You should work with 16- or 32-bit data when doing quantitative attribute analyses.

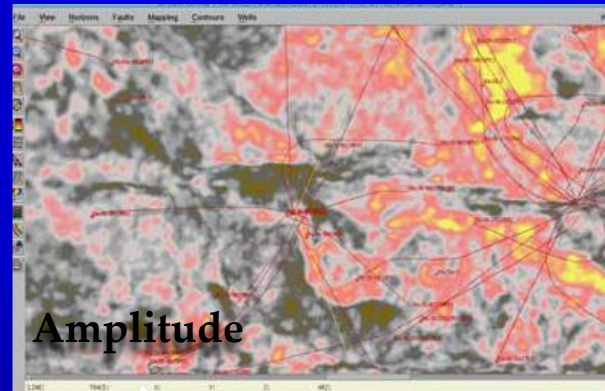
Seismic Attributes

Attributes Combination

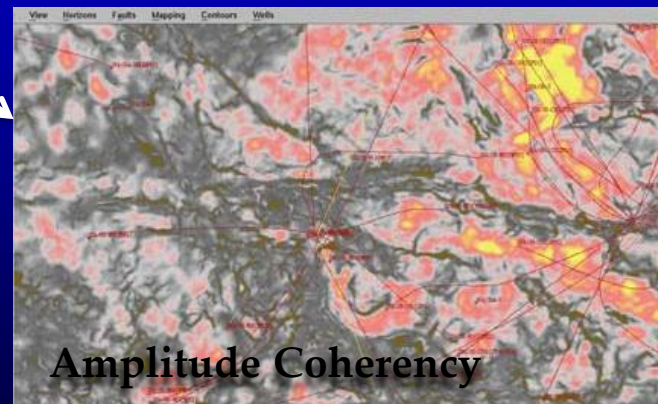
- Attributes may be combined with each other
 - E.g., amplitude-weighted phase
- This helps to combine their effects
- Although simple linear correlations between a physical property and an attribute are sometimes found, relationships are more often non-linear (e.g., Hart and Chen, 2004) and more than one attribute is needed predict the physical property of interest

Seismic Attributes

Attributes Combination



Multiplying coherency (semblance) by amplitude makes structural and stratigraphic features more distinctive - in this case fault arrays and meandering turbidities channels [Shiehallion].



Seismic Attributes

Horizon Slice

Advantages

- Focuses on reservoir or other zone of interest
- Illuminates depositional environment at a fixed geologic time
- Avoids low coherence “structural leakage” due to steep dip
- Steers coherence calculation along an interpreter-defined dip/azimuth, resulting in generally sharper contact images

Disadvantages

- Analysis limited to only a few discrete horizons, which are time consuming to pick
- Analysis limited to the extent of the interpreted horizon
- Picking errors can bias the result or create artifacts
- Some geological surfaces simply cannot be characterized by peaks, troughs, or zero crossings

Seismic Attributes

Time Slice

Advantages

- **Focuses on reservoir or other zone of interest**
- **Illuminates depositional environment at a fixed geologic time**
- **Avoids low coherence “structural leakage” due to steep dip**
- **Steers coherence calculation along an interpreter-defined dip/azimuth, resulting in generally sharper contact images**

Disadvantages

- **Analysis limited to only a few discrete horizons, which are time consuming to pick**
- **Analysis limited to the extent of the interpreted horizon**
- **Picking errors can bias the result or create artifacts**
- **Some geological surfaces simply cannot be characterized by peaks, troughs, or zero crossings**

Seismic Attributes

Spectral Decomposition

Uses the discrete Fourier transform to:

- quantify thin-bed interference, and
- detect subtle discontinuities.

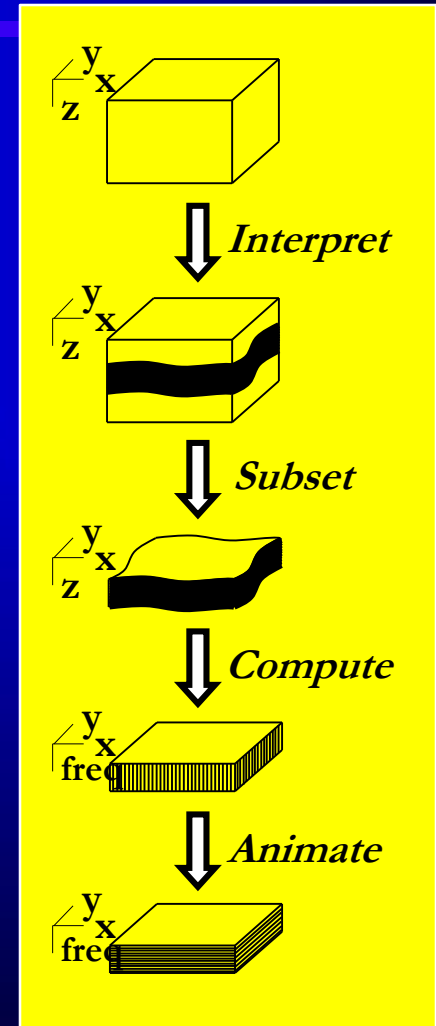
3-D Seismic Volume

Interpreted
3-D Seismic Volume

Zone-of-Interest
Subvolume

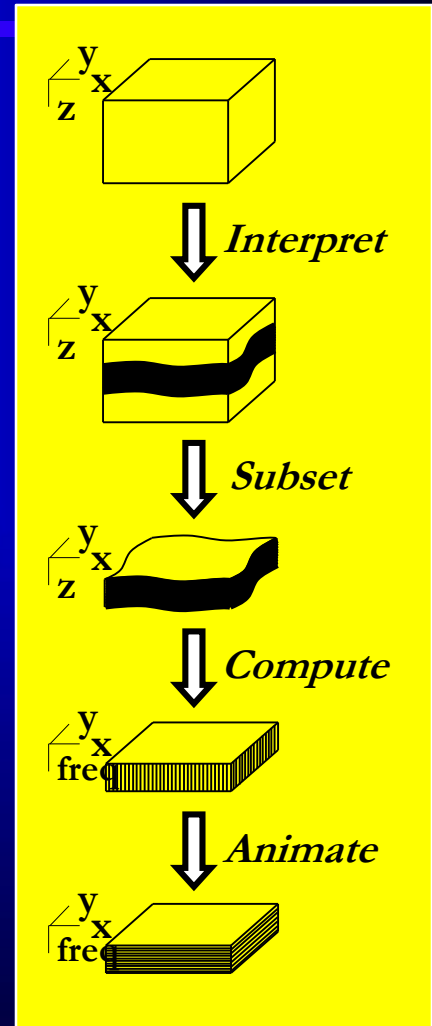
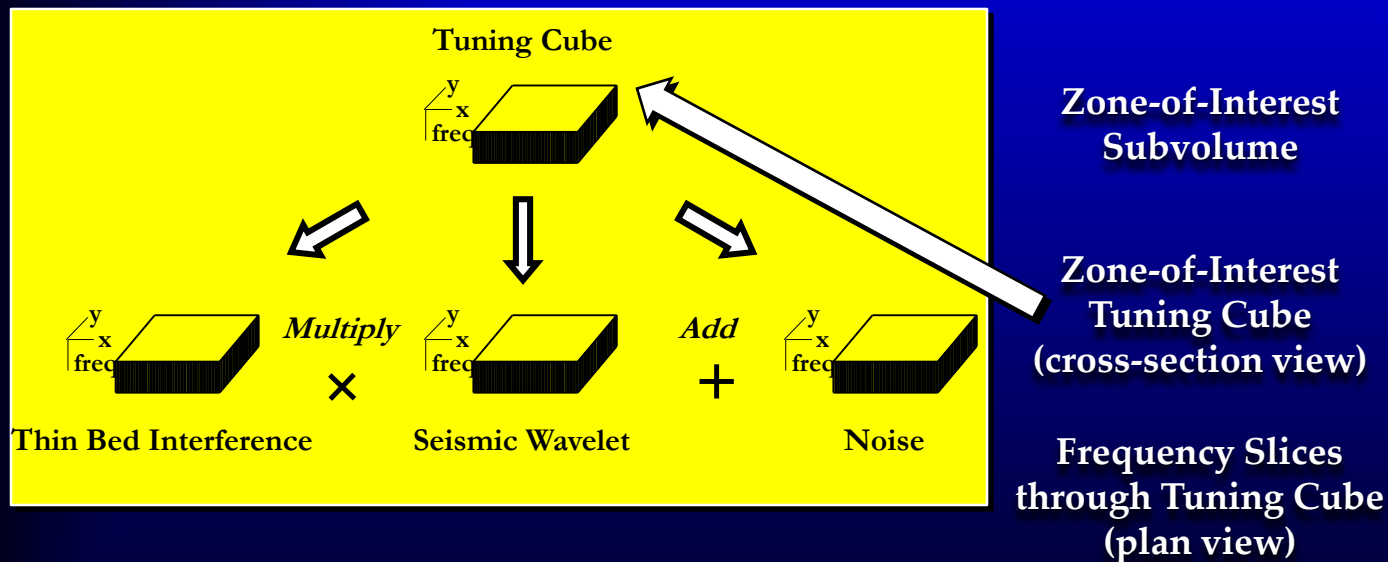
Zone-of-Interest
Tuning Cube
(cross-section view)

Frequency Slices
through Tuning Cube
(plan view)



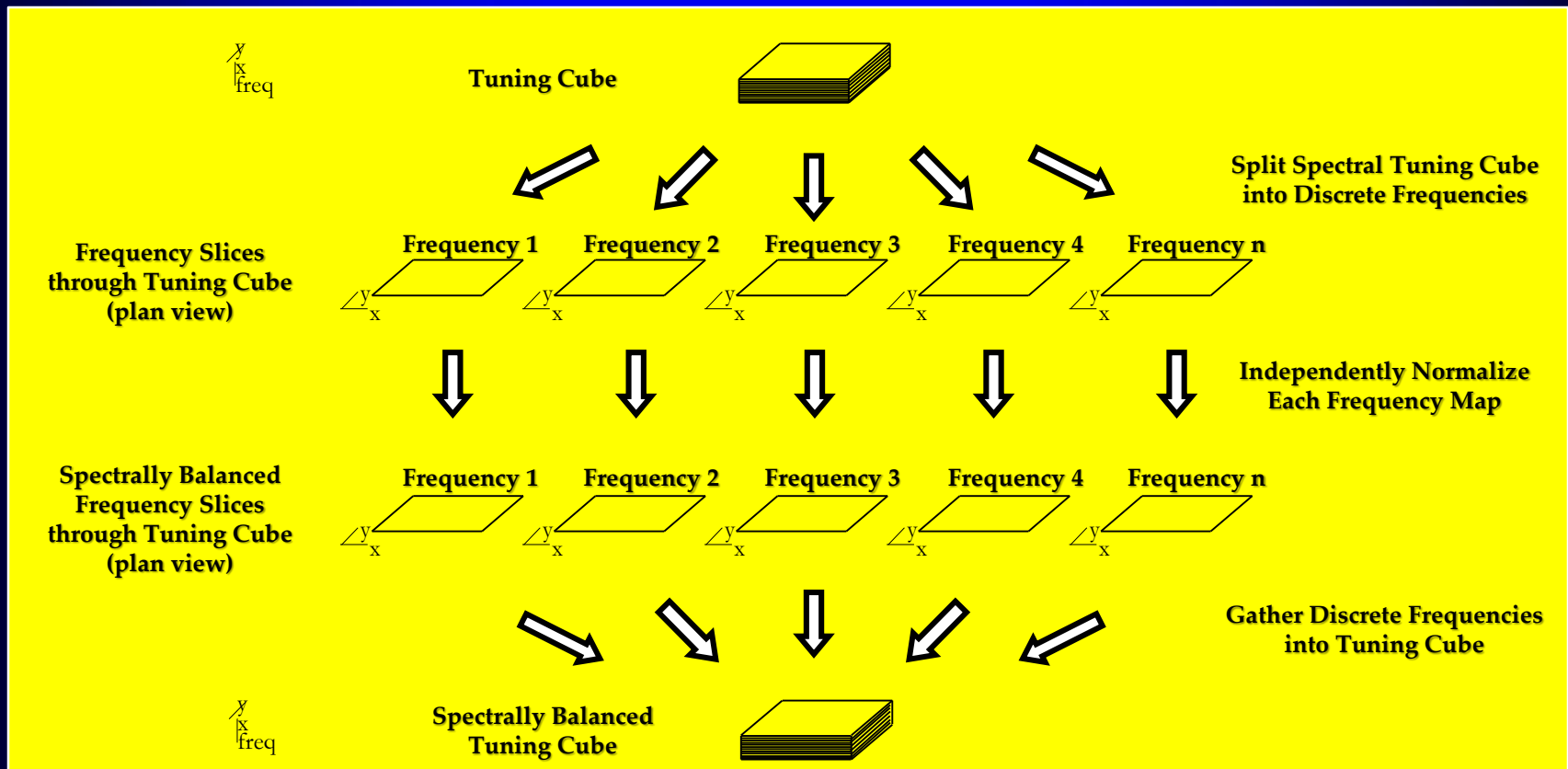
Seismic Attributes

Spectral Decomposition



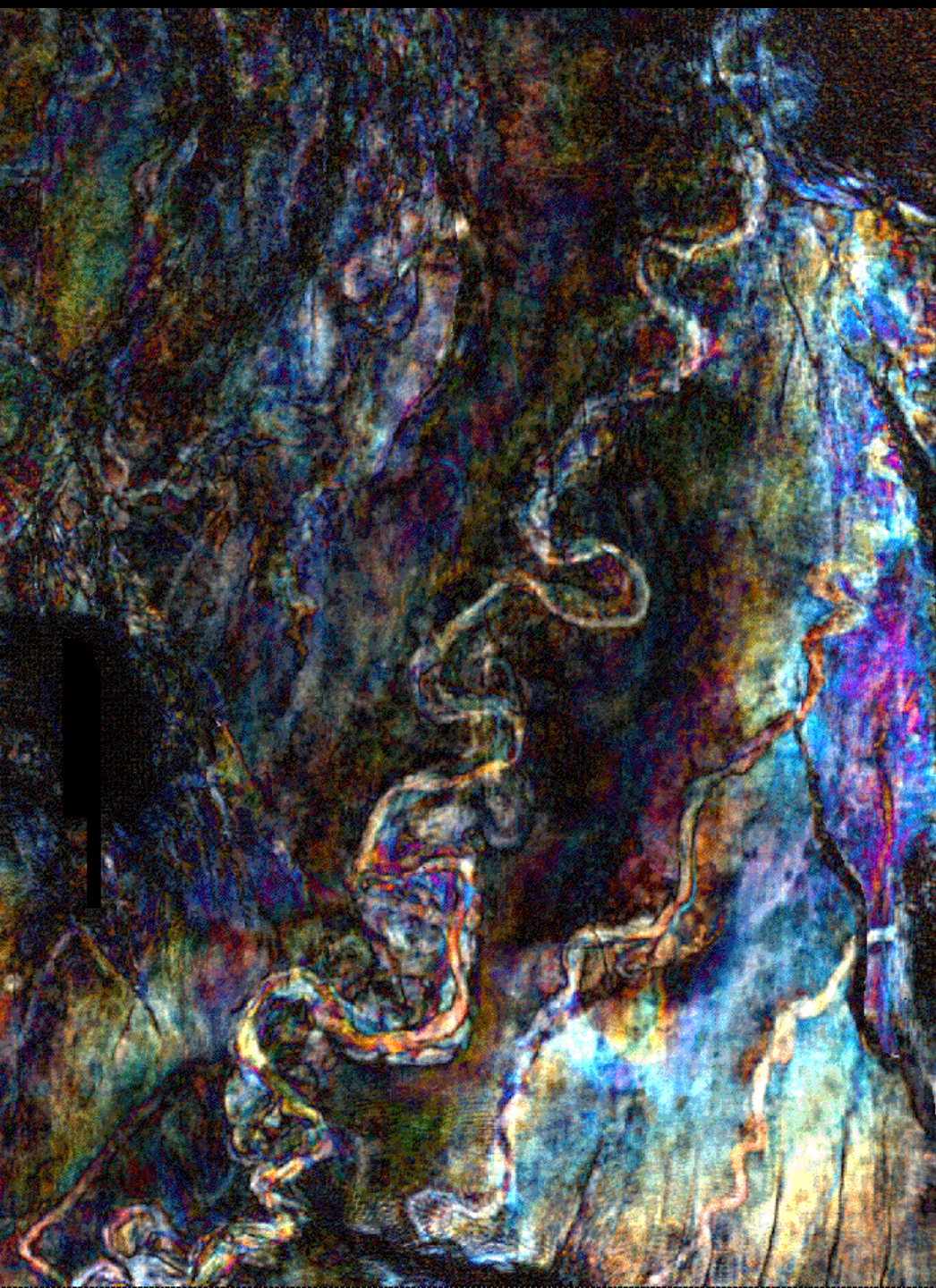
Seismic Attributes

Spectral Decomposition



Seismic Attributes

Spectral Decomposition
Real Data Example
Offshore Africa



spectral decomposition

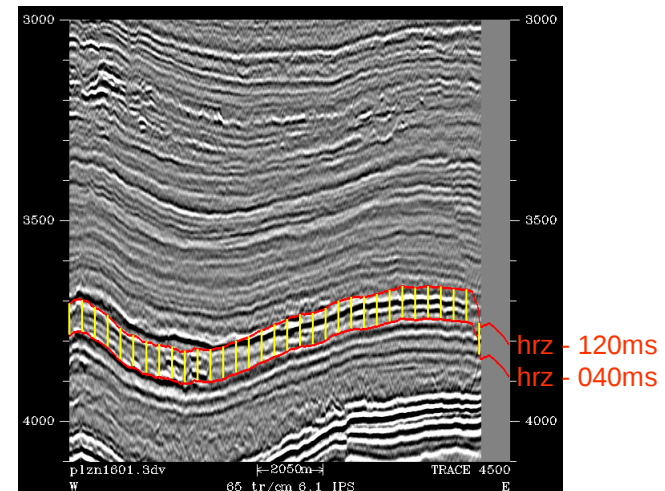
80ms analysis window

centred 80ms above
a picked horizon

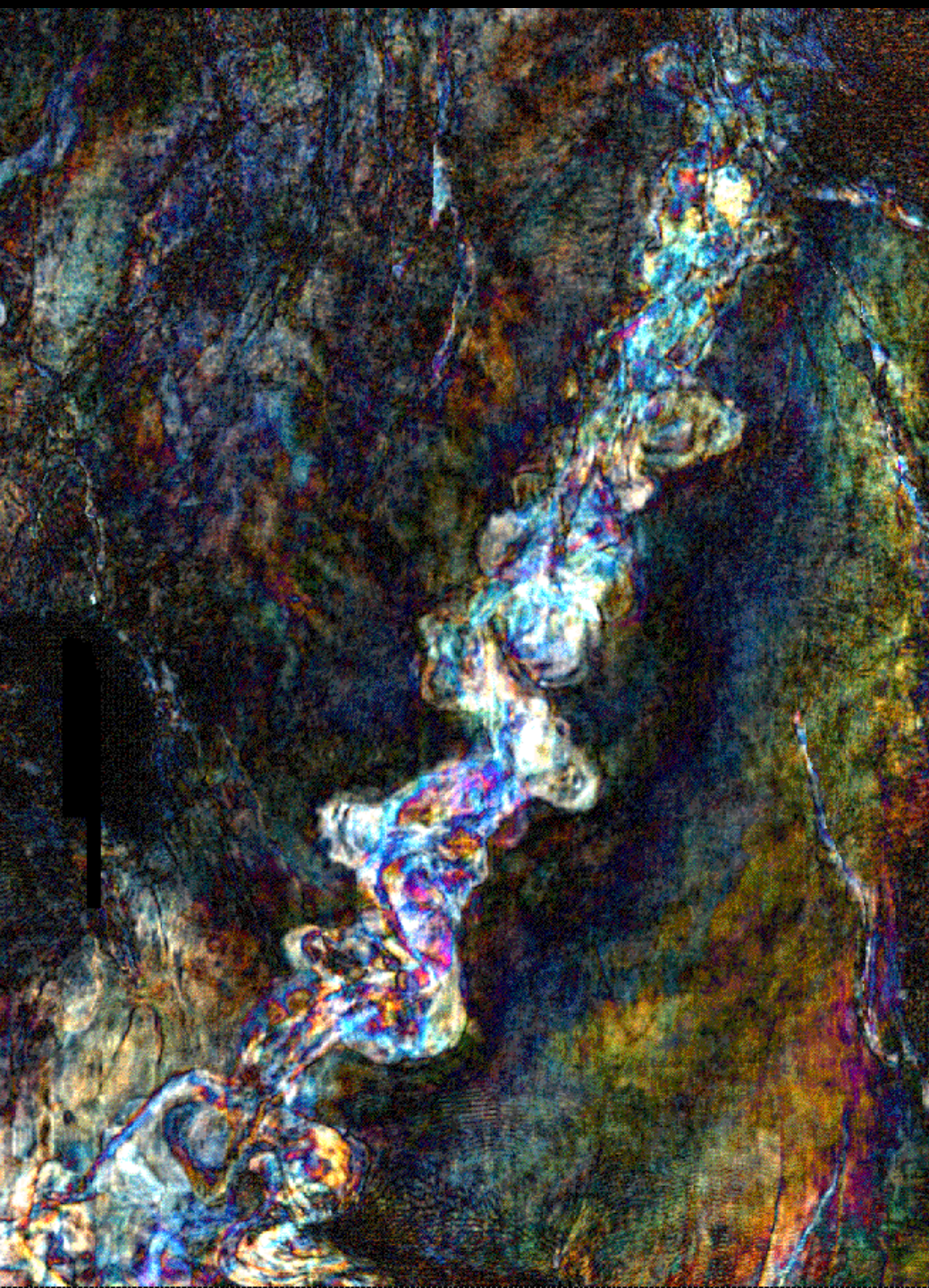
Red = 60hz amplitude

Green = 50hz amplitude

Blue = 40hz amplitude



Courtesy of Lantz, Aluvihare and Partyka



spectral decomposition

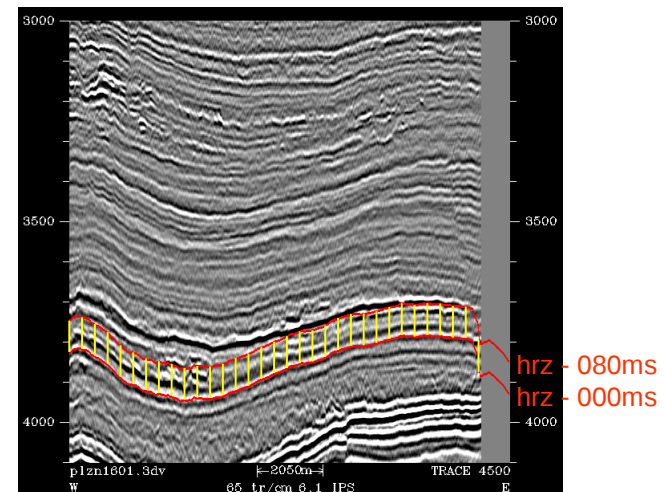
80ms analysis window

centred 40ms above
a picked horizon

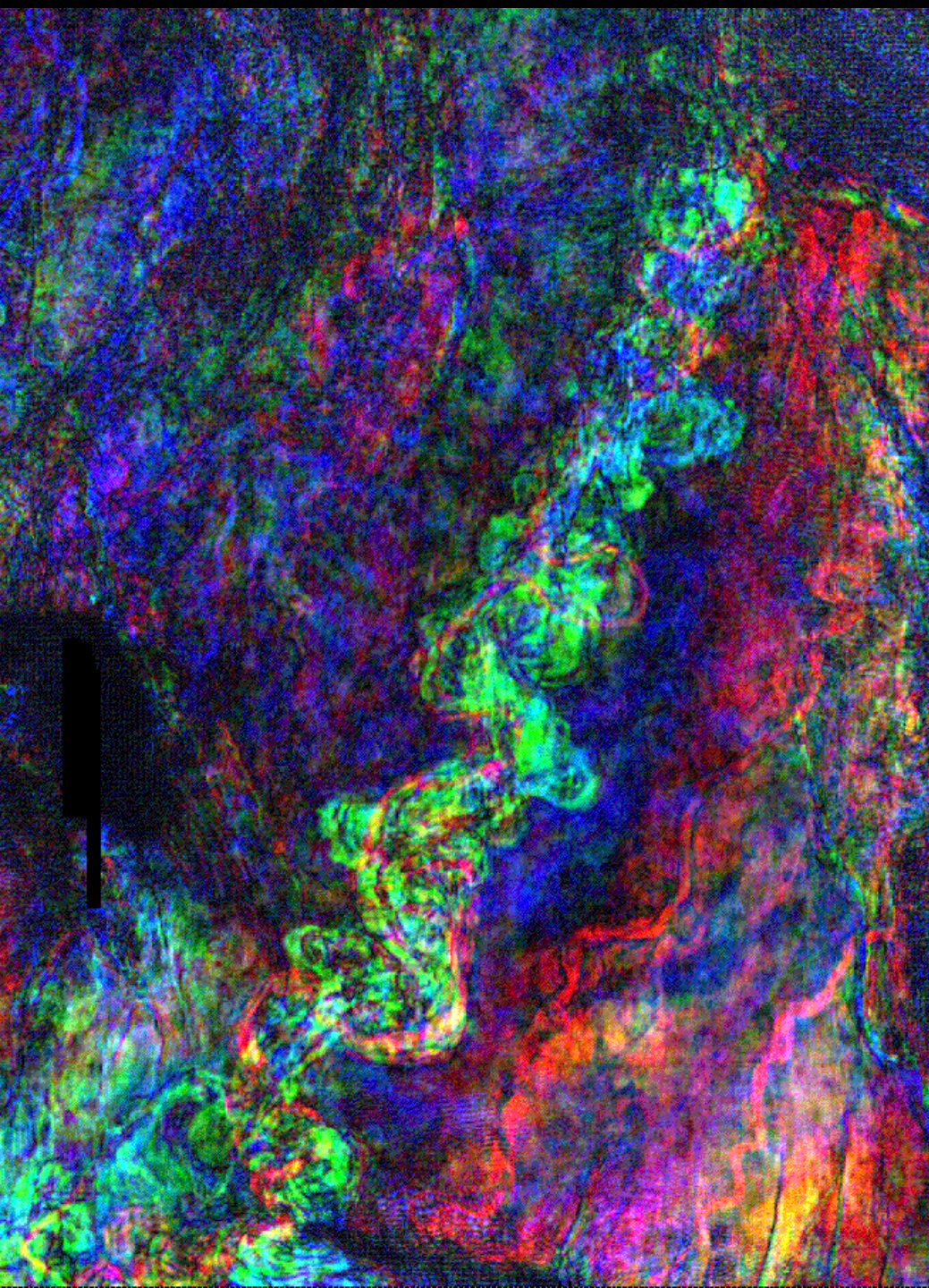
Red = 60hz amplitude

Green = 50hz amplitude

Blue = 40hz amplitude



Courtesy of Lantz, Aluvihare and Partyka



spectral decomposition
60hz amplitude
analysis window = 80ms

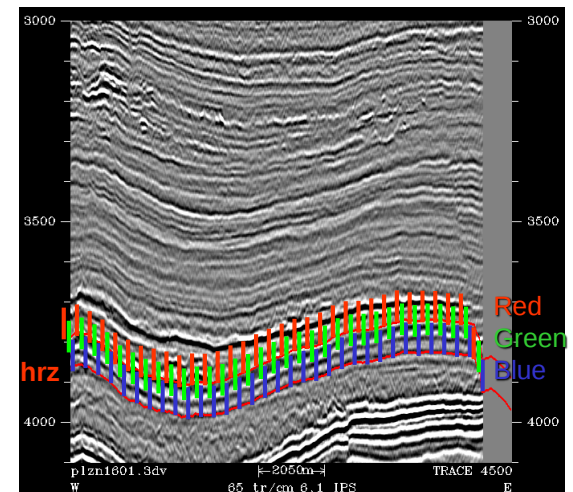
Centred:

80ms above the picked hrz

40ms above the picked hrz

00ms above the picked hrz

youngest → *oldest*
higher → *lower*



Courtesy of Lantz, Aluvihare and Partyka

Seismic Attributes

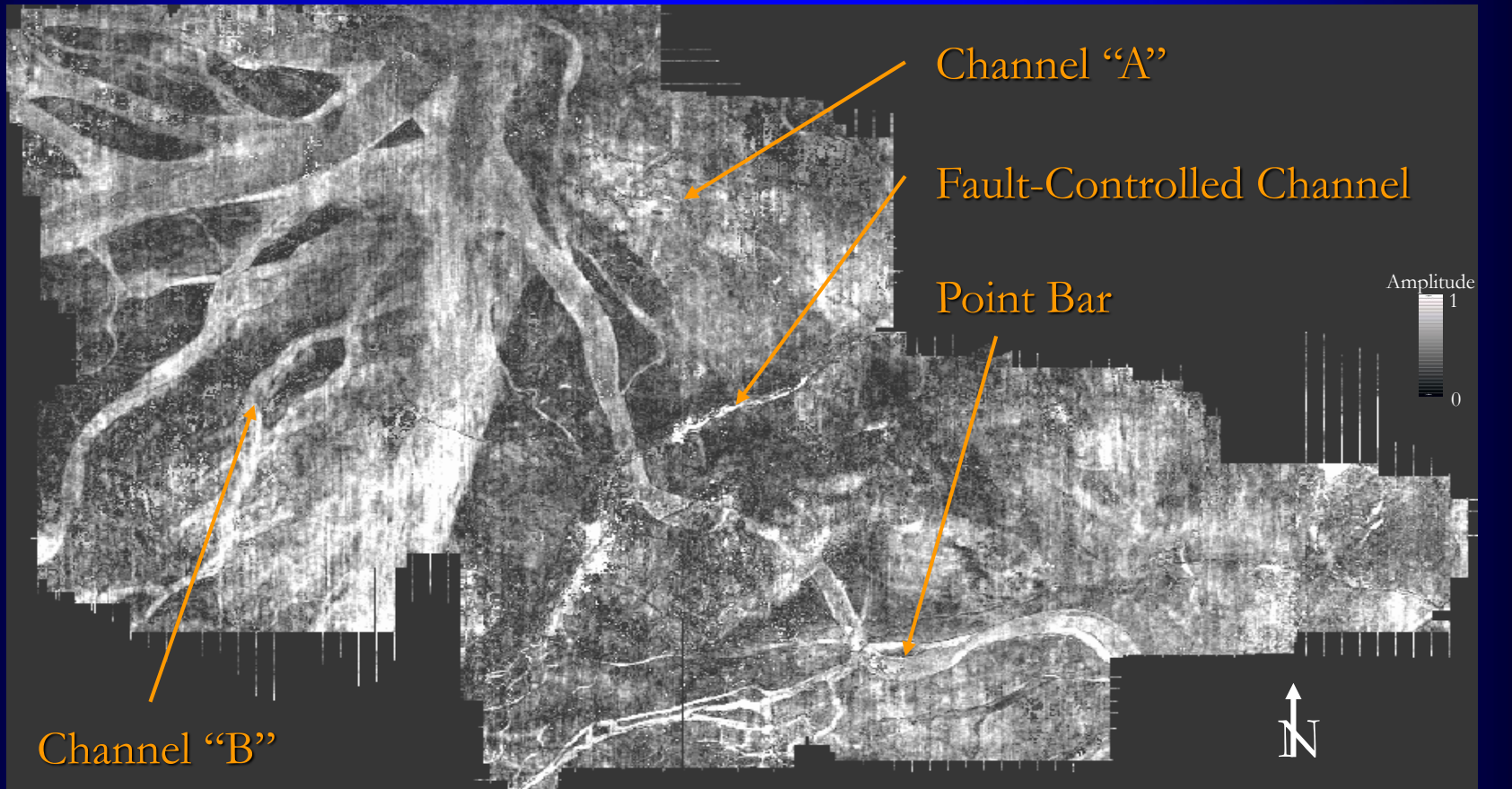
Spectral Decomposition

Real Data Example

Gulf of Mexico , Pleistocene age equivalent

Of modern day Mississippi River Delta

Seismic Attributes

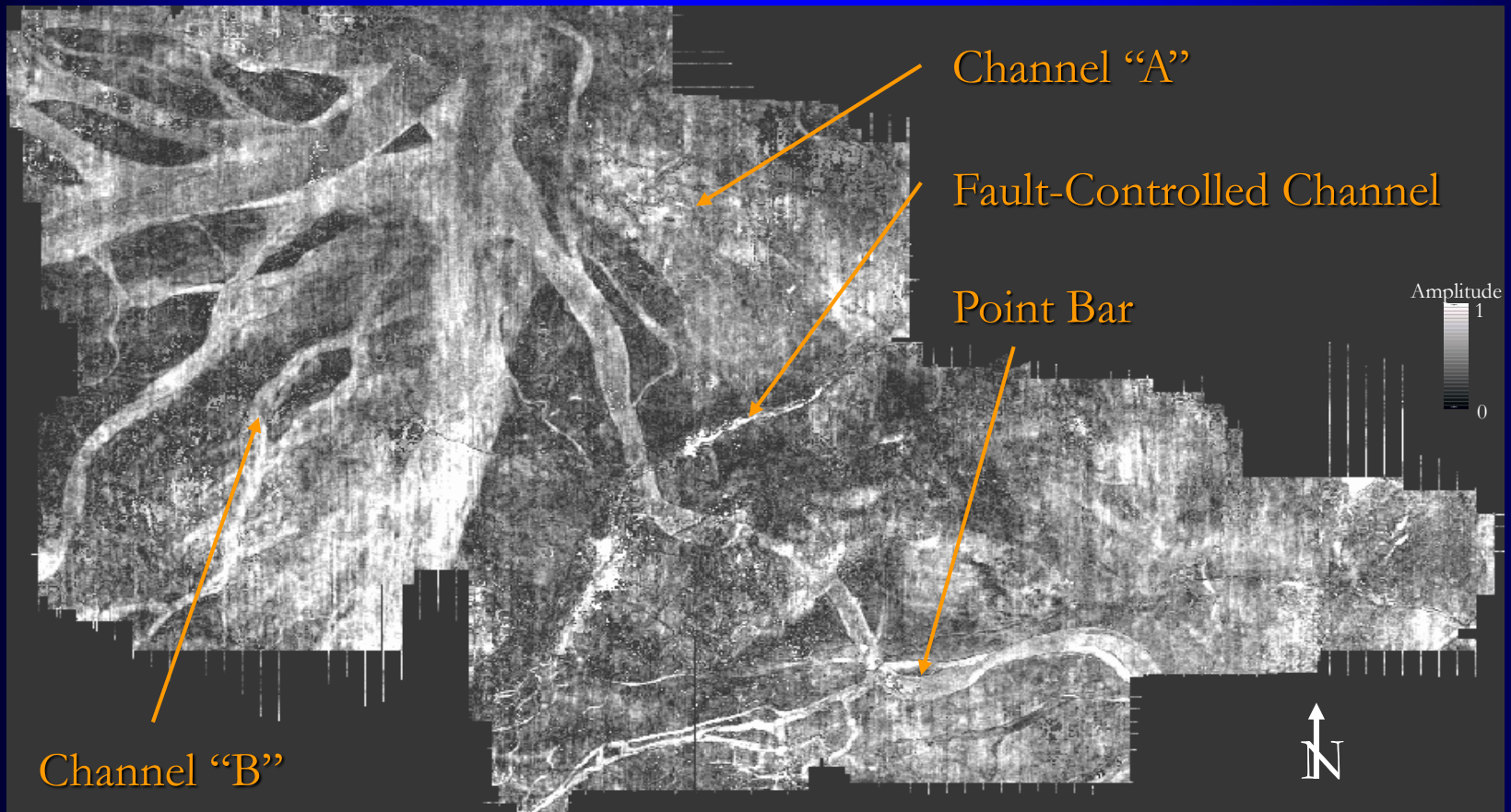


Gulf of Mexico Example

10,000 ft

analysis window length = 100ms

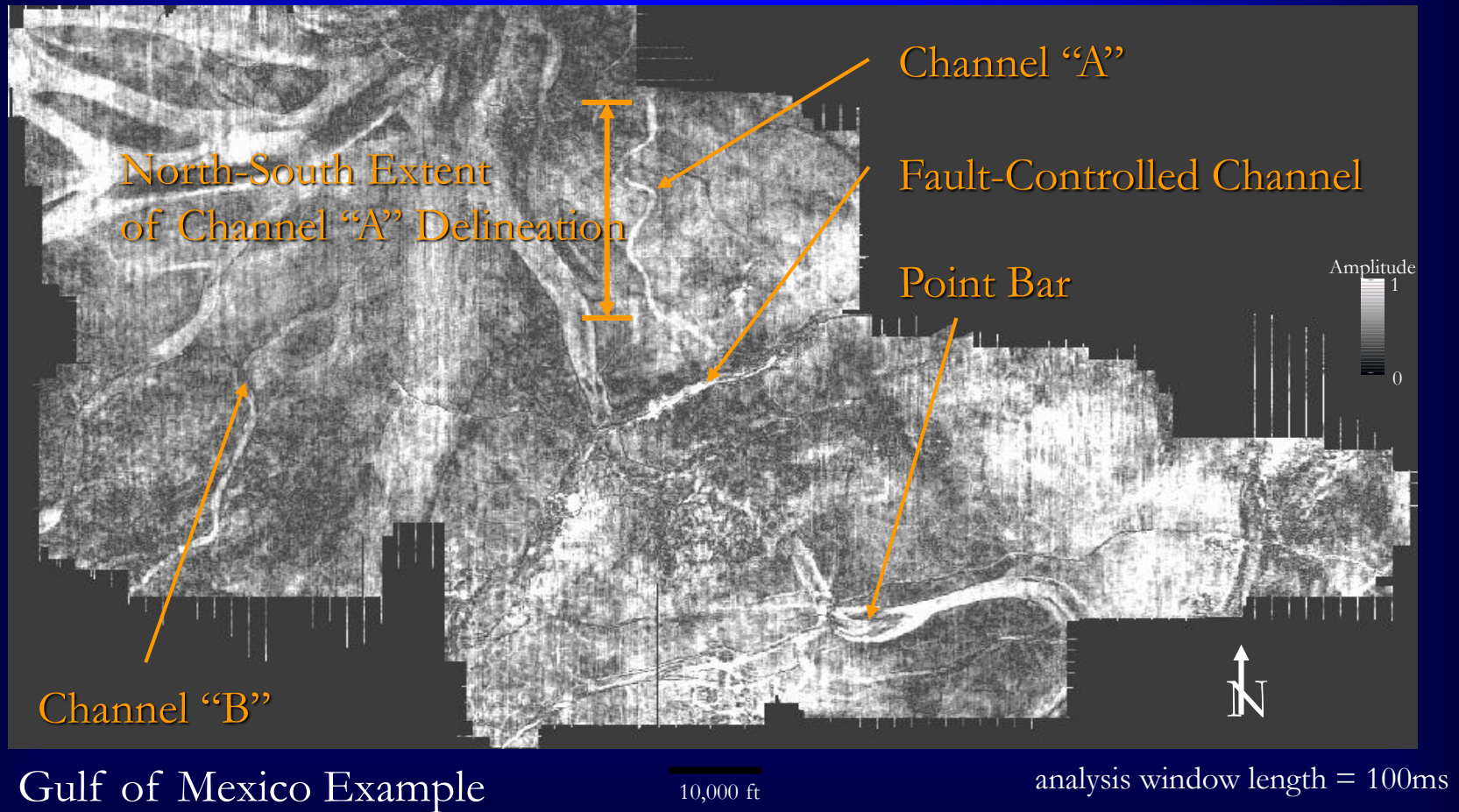
Seismic Attributes



Gulf of Mexico Example

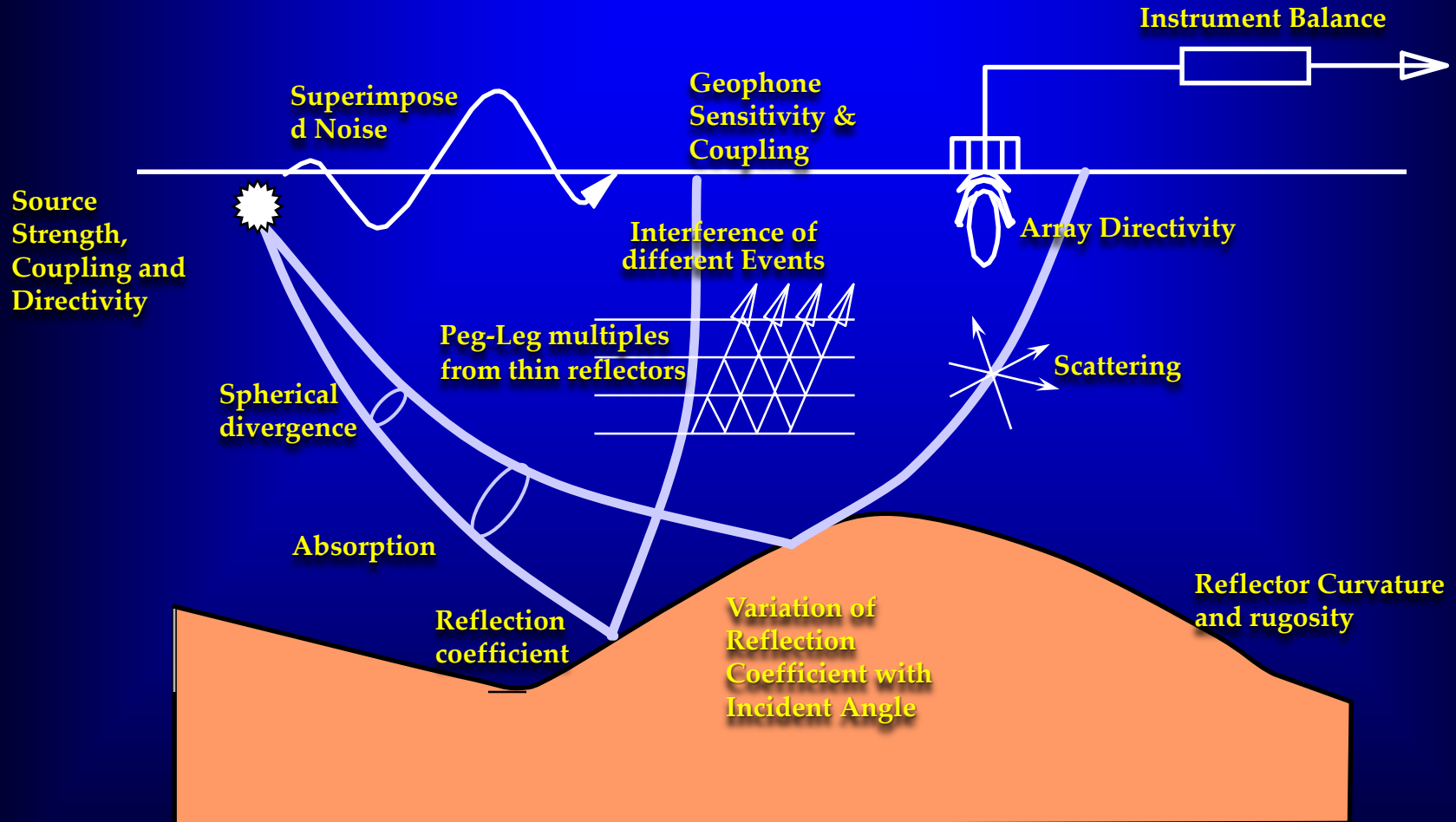
analysis window length = 100ms

Seismic Attributes



3- AVO

Factors Affecting Amplitudes



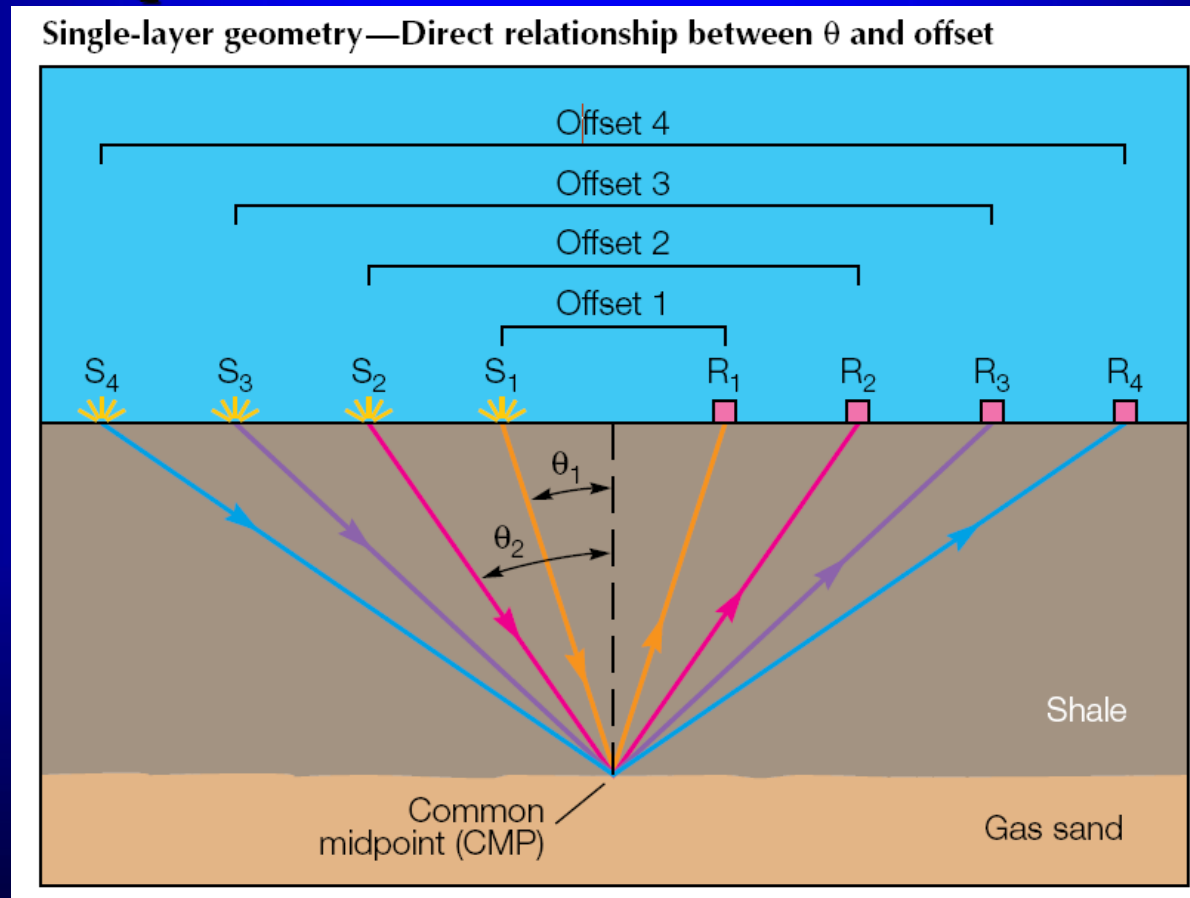
AVO

AVO definition

The variation in the amplitude of a seismic reflection with source-geophone distance. Depends on the velocity, density and Poisson ratio contrast. Used as a hydrocarbon indicator for gas because a large change in Poisson's ratio (as may occur when the pore fluid is a gas) tends to produce an increase in amplitude with offset.

4-AVO Implications

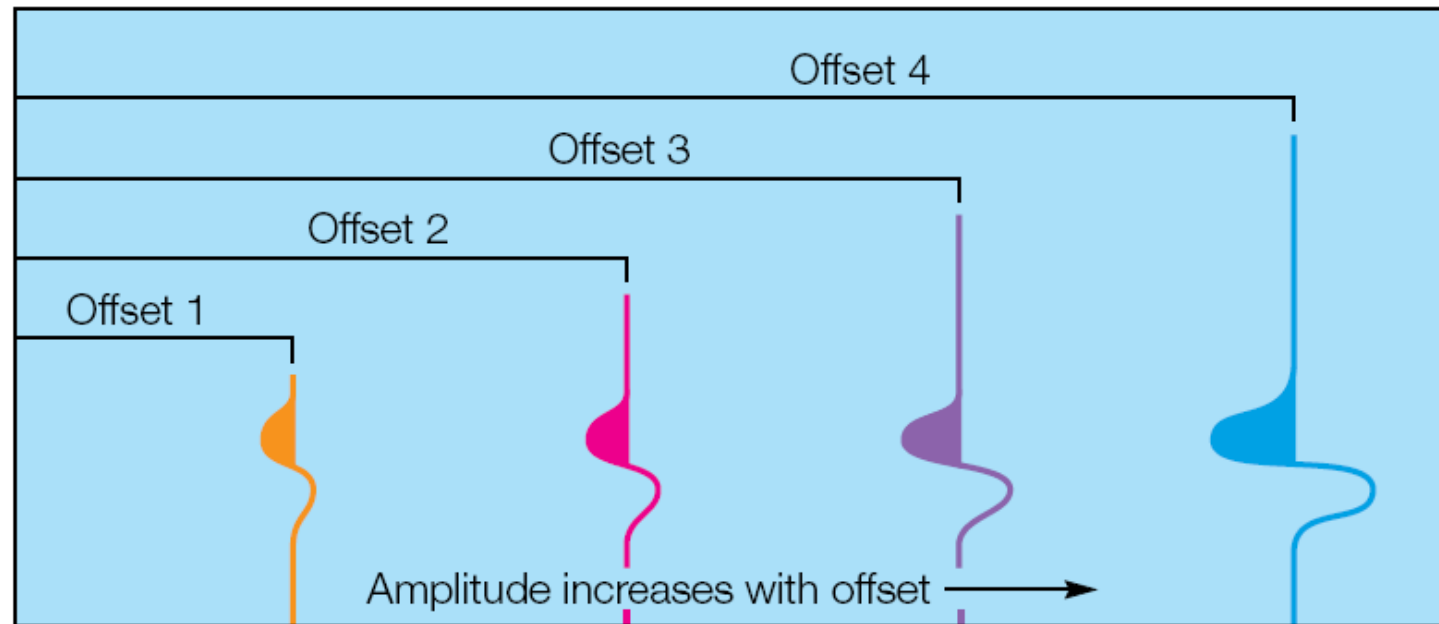
AVO principles



AVO

AVO principles

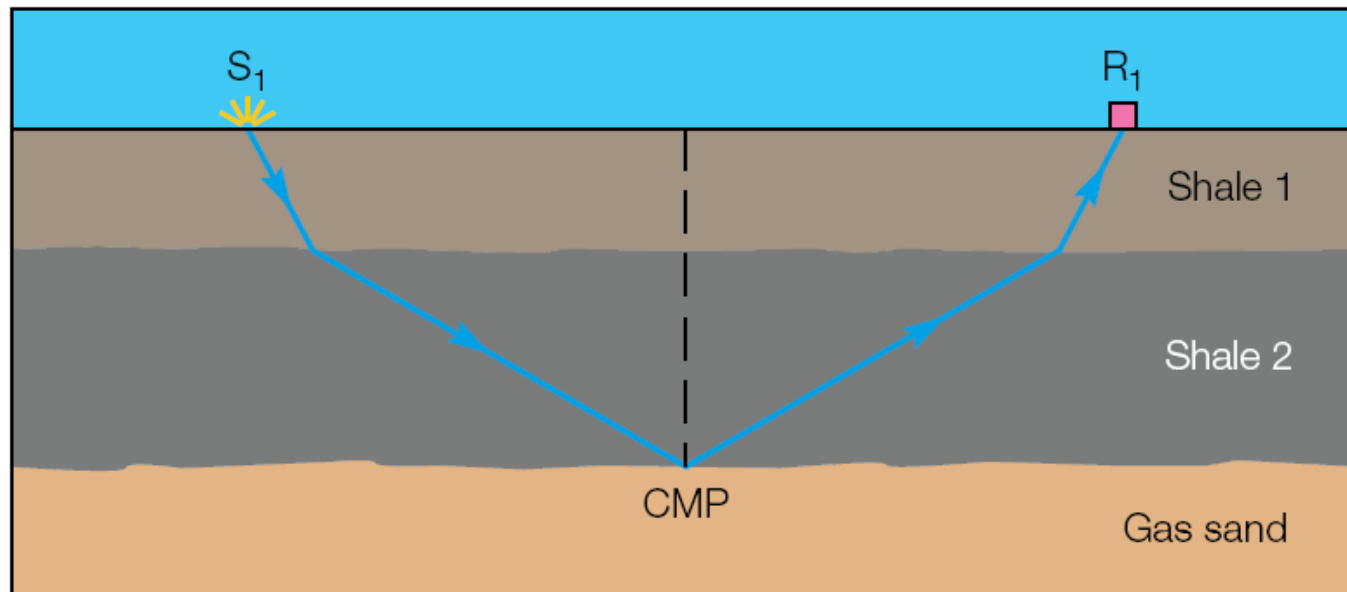
Synthetic traces—CMP gather



AVO

AVO principles

Multilayer geometry—Complex relationship between θ and offset



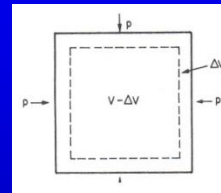
AVO

Modulus = Stiffness
(Stress/Strain Ratio)

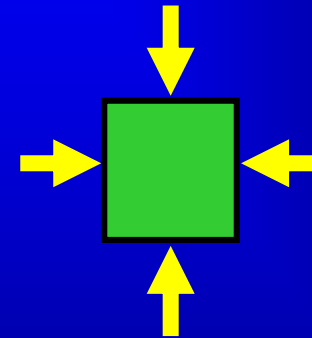
Bulk Modulus κ (incompressibility)
Response to Compressive Stress

Change in Pressure
Relative Change in Volume (Dilatation)

- Bulk modulus – measure of compressibility of rocks and fluids
- Change in volume, not in shape



Dilatation (volume strain)
$$\Delta = \frac{\Delta V}{V}$$

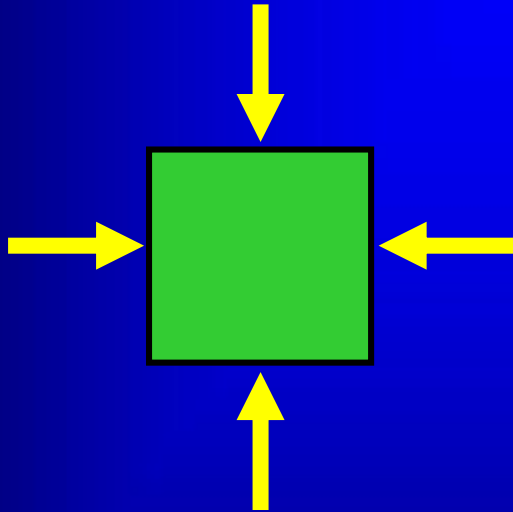


- Shear modulus – measure reluctance to change shape
- Change in shape, not in volume

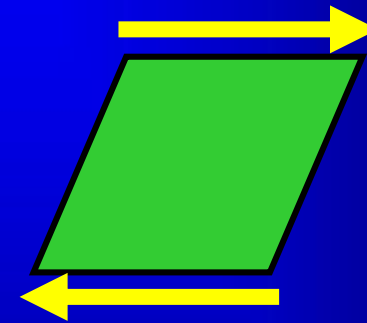
Shear Modulus μ (rigidity)
Response to Shear Stress
Change in Shear Force per unit area
Relative Displacement



AVO



$$V_P = \sqrt{\frac{K + 4\mu/3}{\rho}}$$



$$V_S = \sqrt{\frac{\mu}{\rho}}$$

AVO

AVO principles

Poisson's ratio

Poisson's ratio is simply a measure of how much the cross-section of a rod changes when it is stretched. In a fluid, doubling the length halves the width (the volume is retained) which yields a Poisson's ratio of 0.5. A rod which never got any thinner, regardless of the amount of stretching applied, would have a Poisson's ratio of zero. There is a simple relationship between the P-wave velocity, the S-wave velocity and Poisson's ratio...

AVO

- Definition of Poisson's ratio



Poisson's ratio is the ratio of transverse contraction strain to longitudinal extension strain in the direction of stretching force. Tensile deformation is considered positive and compressive deformation is considered negative. The definition of Poisson's ratio contains a minus sign so that normal materials have a positive ratio.

AVO

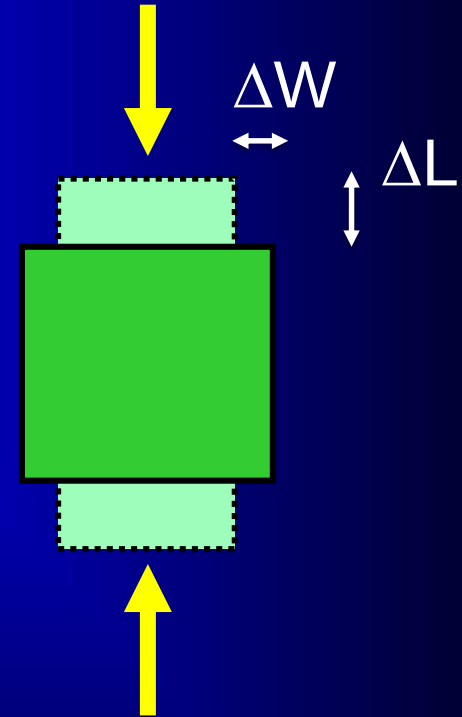
AVO principles Poisson's ratio

$$\sigma = \frac{\text{Relative Change in Width}}{\text{Relative Change in Length}}$$

$$\sigma = \frac{0.5 - (V_S / V_P)^2}{1 - (V_S / V_P)^2}$$

Poisson's ratio is related to V_P/V_S ratio:

$$V_P / V_S = \sqrt{\frac{1 - \sigma}{0.5 - \sigma}}$$



- Bulk modulus k volume stress/strain
- Shear modulus μ shear stress/strain
- Poisson's ratio σ transverse/longitudinal strain
- Young's modulus E longitudinal stress/strain

Seismic Velocities in a homogeneous medium

Can be expressed as function of different combinations of

$K, \sigma, E, \mu, \rho, \lambda$

Often used expressions are:

k = Bulk modulus

σ = Poisson ratio

E = Young's modulus

μ = Shear modulus

ρ = mass density

λ = Lamé's lambda constant

$$v_p = \sqrt{\frac{k + \frac{4\mu}{3}}{\rho}} = \sqrt{\frac{\lambda + 2\mu}{\rho}}$$

$$v_s = \sqrt{\frac{\mu}{\rho}}$$

$$\lambda = k - \frac{2}{3}\mu$$

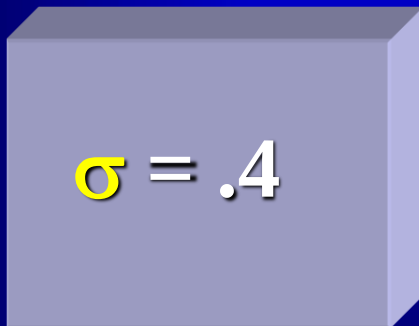
AVO

AVO principles Poisson's ratio

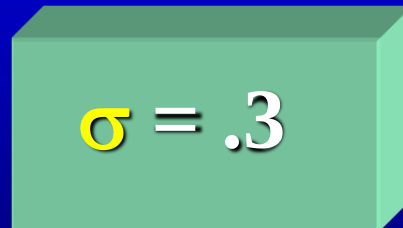
Poisson's Ratio varies : σ

σ may be thought of as a measure of Incompressibility

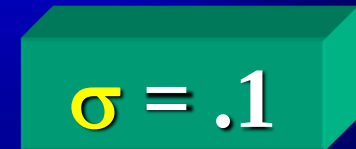
0.5 ← —————→ 0.0



Wet Sand



Oil Sand



Gas Sand

AVO

AVO principles Poisson' ratio

- The shear modulus of a rock does not change when the fluid is changed.
- However, the bulk modulus changes significantly when the fluid changes.
- As such, the p-wave velocity of a rock will change as hydrocarbon saturation changes whereas the s-wave velocity will change relatively little (there is a slight density effect).

Velocity of P waves Depend on

- Matrix and structure of the stone
- Lithology
- Porosity
- Pore filling interstitial fluid
- Temperature
- Degree of compaction
-

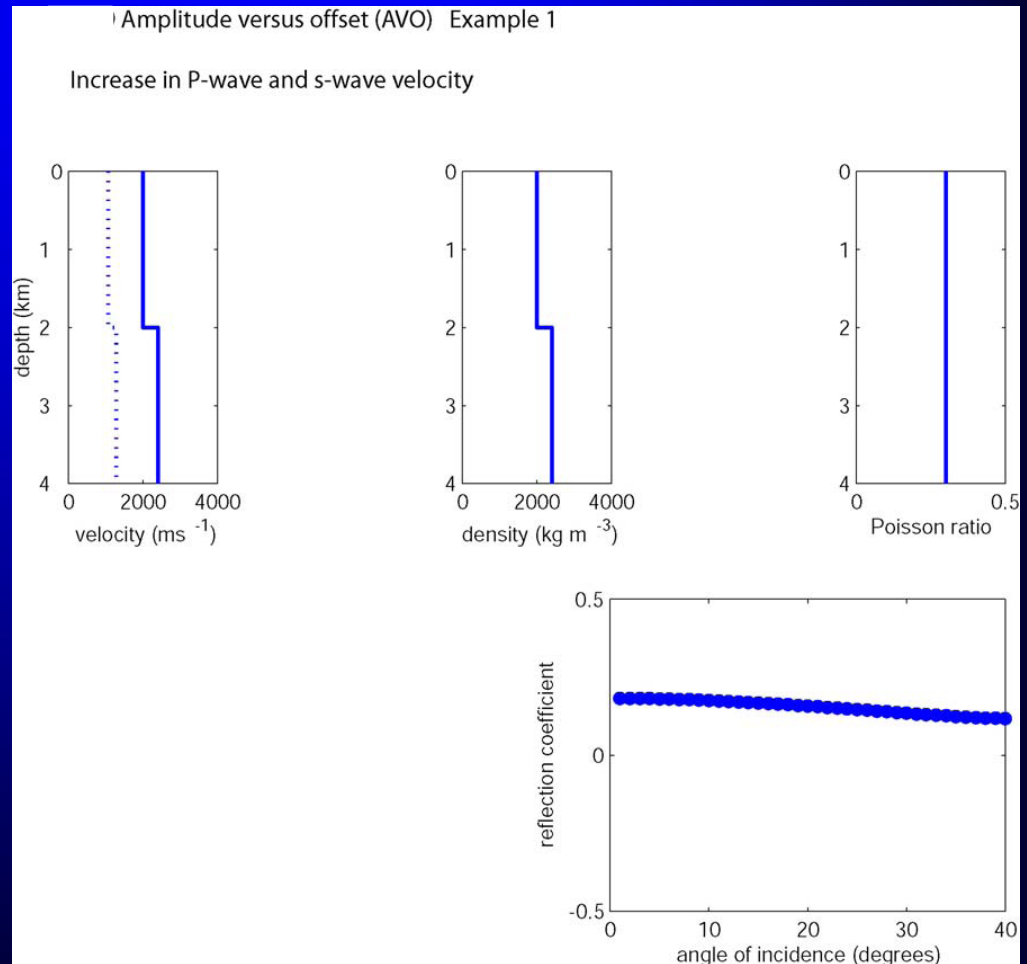
AVO

AVO Assumptions

- No seismic attenuation
- No transmission loss
- No wavelet interference (tuning)
- Amplitude vs angle(θ)
- Large angles
- Pre-stack events flattened
- Seismic Processing
- Q compensation
- Gain function
- Broad amplitude spectrum
- Remove wavelet
- Zero-phase data
- Pre-stack migration
- Map offset to angle, θ
- Avoid offset mute
- Accurate (high-order) NMO correction

AVO

Both P-wave and S-wave velocities increase across the interface. Remember that at non-normal incidence, an incident P-wave will generate 4 new waves. These are the reflected and transmitted P-waves and the reflected and transmitted S-waves. The reflection coefficient of the P-wave decreases with angle in this example.



AVO

This example simulates the effect of shale overlying a gas saturated sand reservoir. The P-wave velocity decreases, giving a negative reflection coefficient at normal incidence.

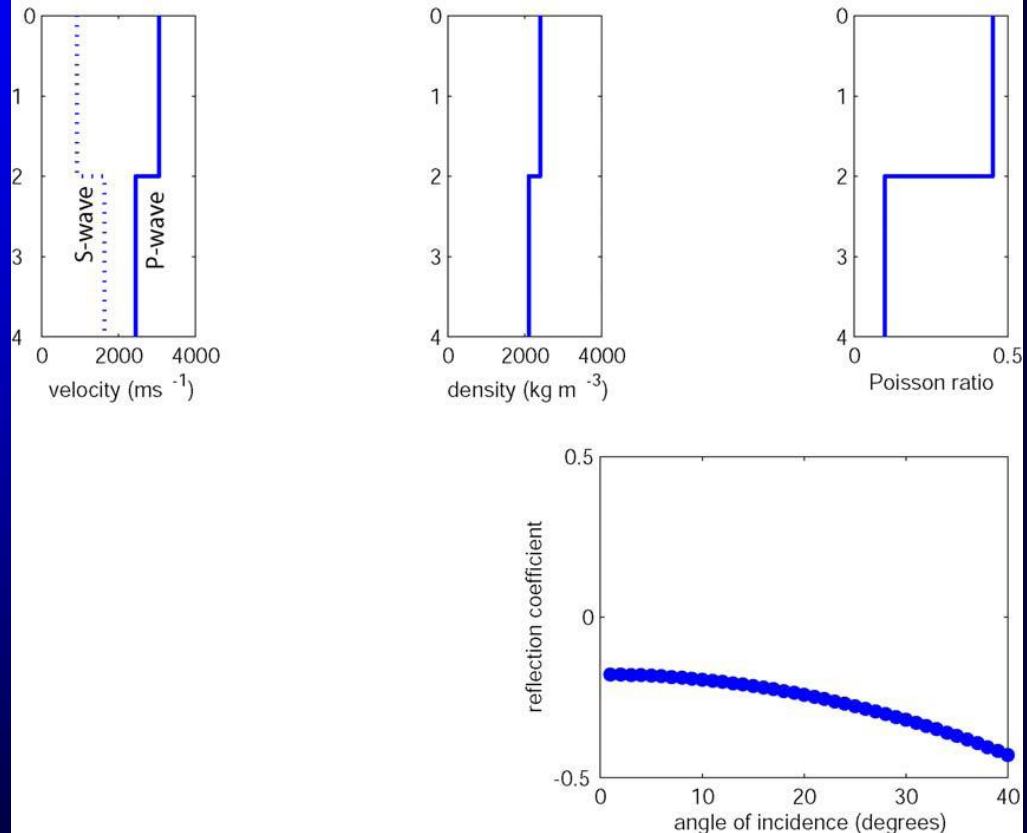
The S-wave velocity increases from the shale into the gas sand. Why?

Can show that this corresponds to a decrease of Poisson's ratio

Poisson's ratio is usually around 0.5 for incompressible materials, and softer material will have values in the range 0 to 0.2. In this case, the P-wave reflection coefficient becomes larger as the angle of incidence increases. Since an increase in angle corresponds to a greater source-receiver offset, this is called an amplitude-versus offset (AVO) anomaly.

Amplitude versus offset (AVO) Example 2

Reflection from the top of gas sand reservoir

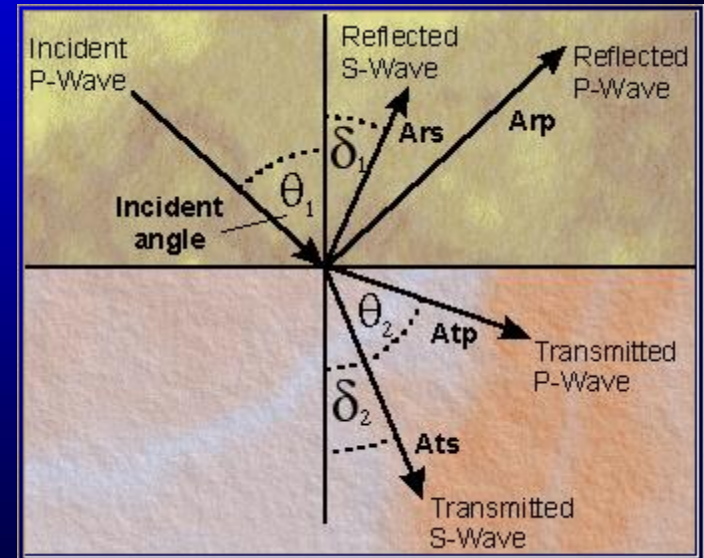


AVO Implications

AVO principles

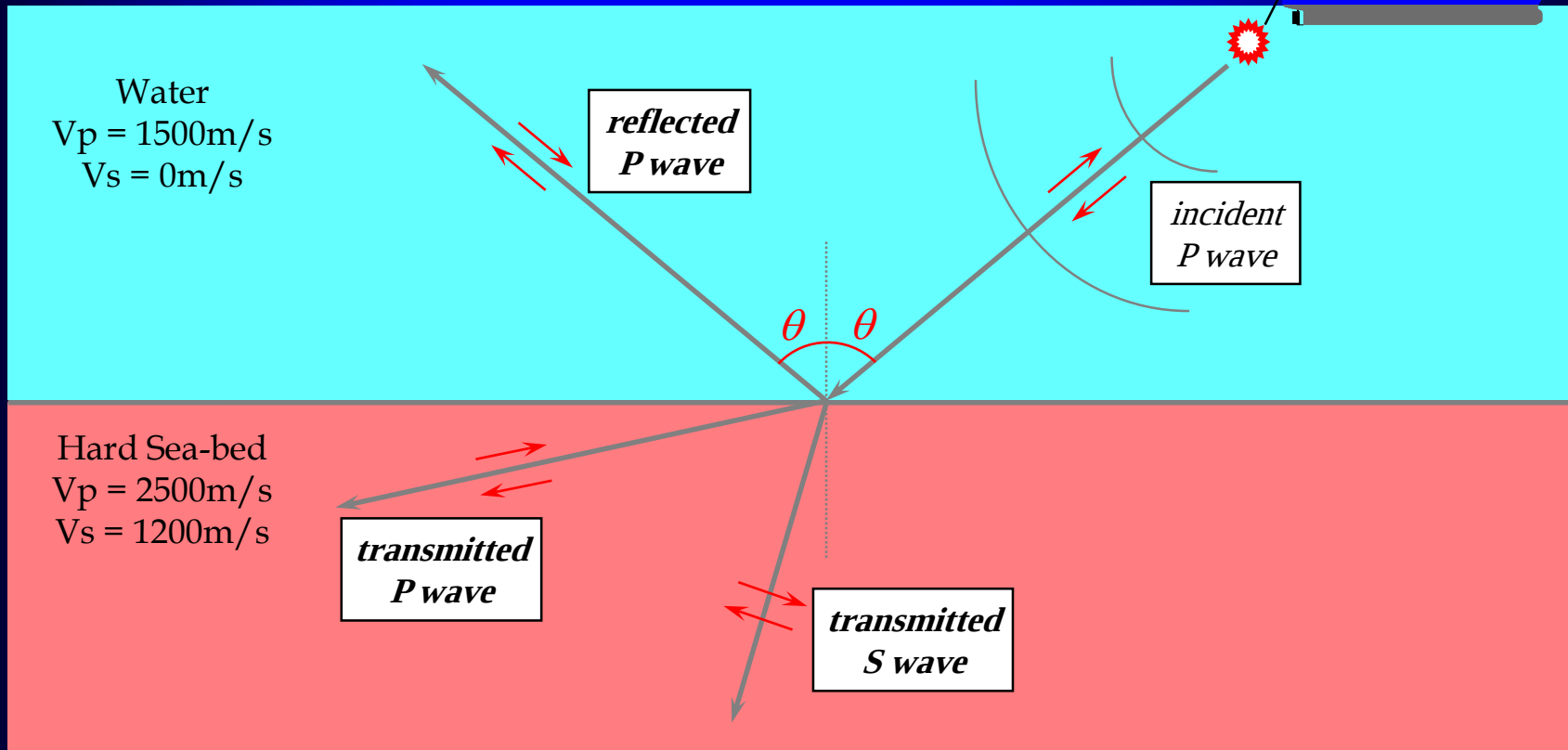
At every reflection in land section - P-waves that are not exactly at right-angles to a reflector partially convert into S-waves which continue on down the section reflecting and refracting.

AVO: is due to partitioning of the sound energy at interface



AVO

P-wave & S-Wave



AVO

- At any point in the sub-surface, there are only three independent acoustic rock properties responsible for seismic reflection :
 - V_p ,
 - V_s ,
 - density
- All attributes we compute will depend on the the spatial distribution of the above three properties.
- From these attributes we would like to infer:
 - Rock Properties
 - Fluid type
 - Porosity/Permeability
 - Pressure

AVO Implications

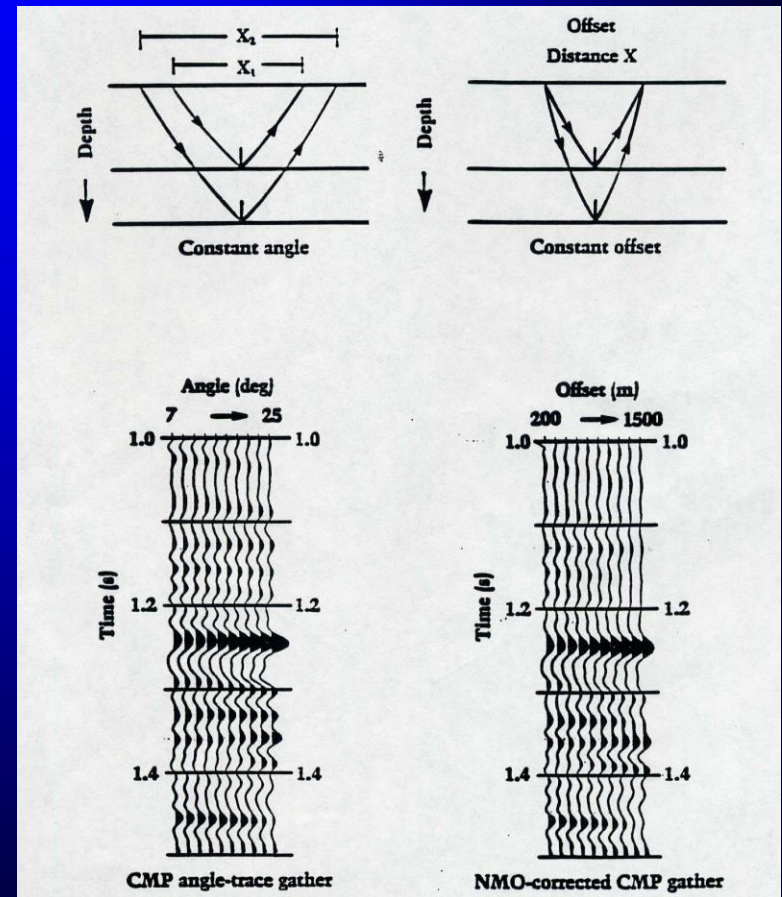
AVO principles

- The AVO technique for DHI is based on two principles:
 1. When Gas replaces brine in reservoir rocks, Poisson's Ratio (V_p/V_s) Decreases.
 2. When Poisson's ratio decreases, R_c and amplitude becomes more negative with increasing angle.

AVO Implications

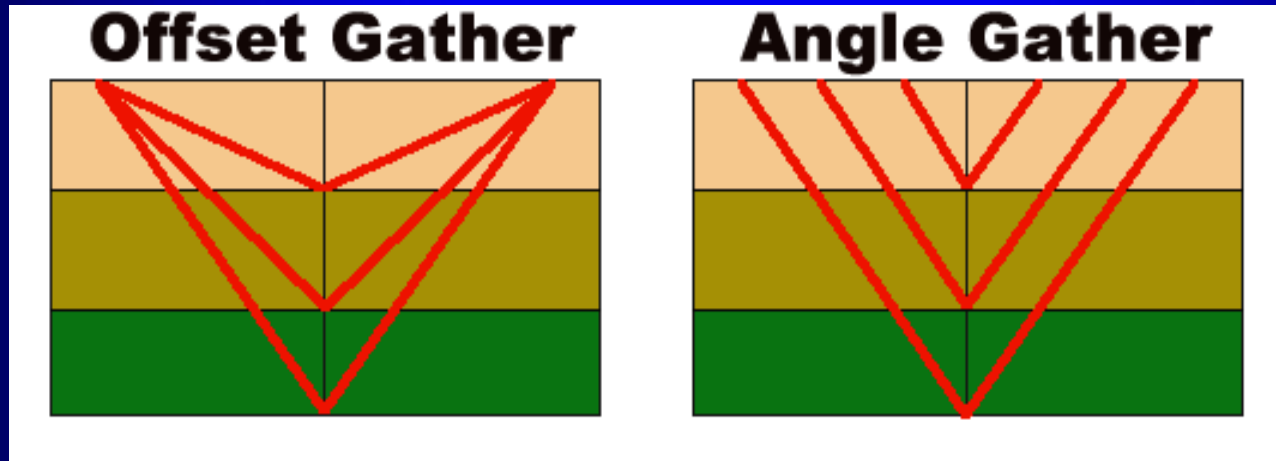
AVO /AVA principles

- Change in Incident Angle -> Change in Amplitude
- Different Offsets, Same Time -> Different Incident Angles -> Different Amplitudes
- Same Offset, Different Times -> Different Incident Angles -> Different Amplitudes
- Amplitude changes with Offset
- Temporal & Spatial change in velocity complicates the proceedings!



AVO

AVO /AVA principles

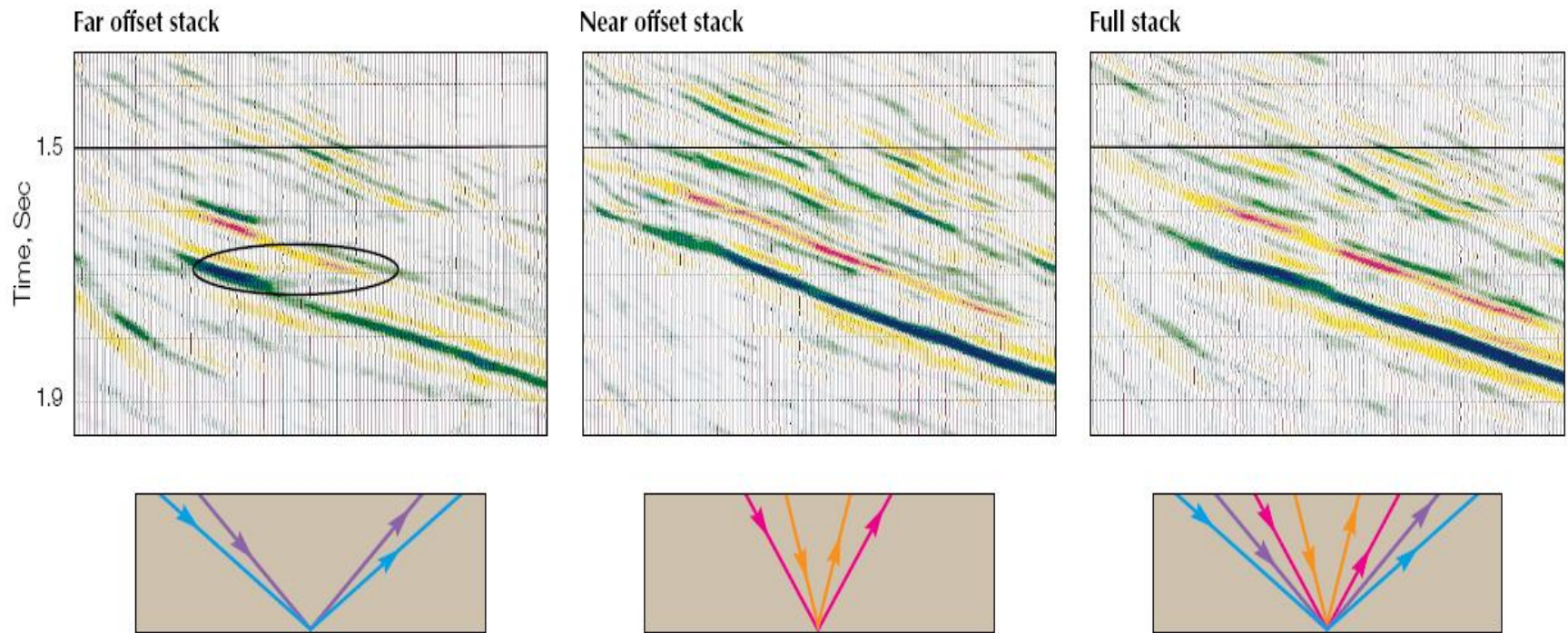


Angle of incidence decreases with depth for constant offset trace

Angle of incidence constant for all depths on a constant angle trace.

AVO

AVO principles



AVO

AVO Parameters

- P-Wave Velocity - Measured :
 - Well logs
 - Seismic Velocity Analysis
- Density - Measured :
 - Well logs
 - Empirically from P-Wave Velocity
- S-Wave Velocity - Difficult to Measure
 - P-Wave velocity/S-Wave velocity Ratio
 - Poisson's Ratio (Rock Property)
 - Multi-component data analysis

AVO checklist

- Is the expected rock properties variation sufficient to produce a detectable AVO anomaly?
- Can the same seismic response result from other earth models?
- If AVO correctly predicts the occurrence of hydrocarbons, what are the chances that the saturation will be commercial?
- Is there sufficient angular coverage for the event of interest?
- How do I know that processing has preserved and isolated the "true" relative AVO response?
- What is the seismic data quality?
- Overburden? Processing?
- Does the AVO anomaly conform the structure?
- Do I understand what "red" on the AVO display really means in physical terms

AVO misconceptions

Myth

- AVO does not work
- Gas-sand amplitude increases with offset
- AVO can not be used to detect oil sands
- AVO does not work in carbonates
- Land AVO is more difficult than marine AVO
- V_p/V_s is 1.6 for brine sands, 1.8 for dolomites, 1.9 for limestones, and 2 for shales
- R_p and R_s are readily extracted from $R(0)$

Reality

- AVO does work under the right circumstances
- Gas-sand reflection coefficients generally become more negative with increasing of offset.
- High GOR light oil-saturated rocks may exhibit significant AVO anomalies
- There are some applications
- The marine short-period multiples are still a problem
- V_p/V_s varies significantly
- R_p and R_s can be extracted from $R(0)$ and G if V_p/V_s is known

AVO

In basins where the geologic section is relatively young and unconsolidated-water, oil, and/or gas response may be seen in amplitude studies-DHI's.

- Gas or light oil can significantly decrease the Acoustic Impedance of a porous zone versus a brine fill.
- The anomalous amplitude should conform to a trap configuration.
- The hydrocarbon-water contact may occur as a flat reflection.
- Area and thickness of a seismic hydrocarbon anomaly may be used for pre-drill volumetric estimates

Some conclusions

- For large negative P-wave reflection coefficients, gas-sand and brine-sand reflection coefficients are distinct for all shale velocities. The lower the shale velocity, the greater the separation.
- For small P-wave reflection coefficients, gas-sand and brine-sand reflection coefficients are well separated only for low shale velocities and only if the shale velocity is approximately known.
- For large positive P-wave reflection coefficients, gas-sand and brine-sand reflection coefficients are well separated only for the lowest shale velocities and only if shale velocity is approximately known

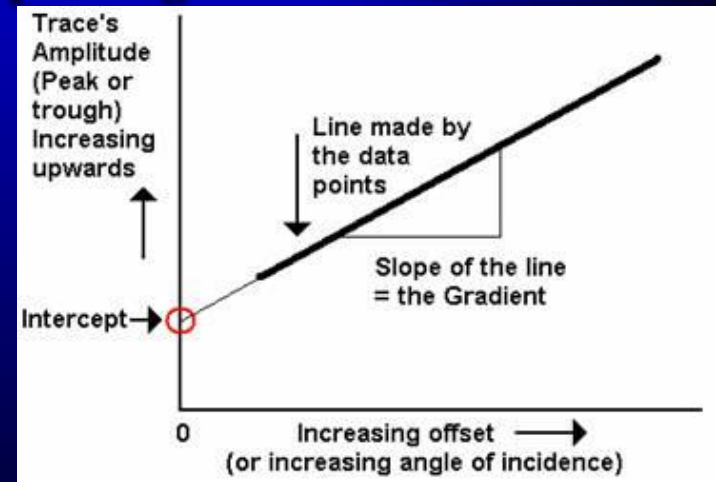
AVO

AVO Attributes

If we measure the amplitude of each reflection amplitude as a function of offset, and plot them on a graph as a function of the sine of angle of incidence squared, we observe a straight line. For any line, the intercept and gradient can be measured. By linearizing the complicated mathematics behind the AVO technique, Richards and Frasier (1976) and Wiggins et al (1986) gave us the following physical interpretation of the intercept and gradient:

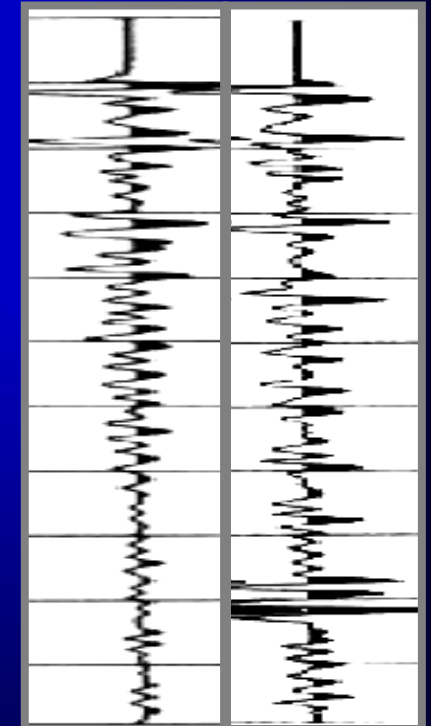
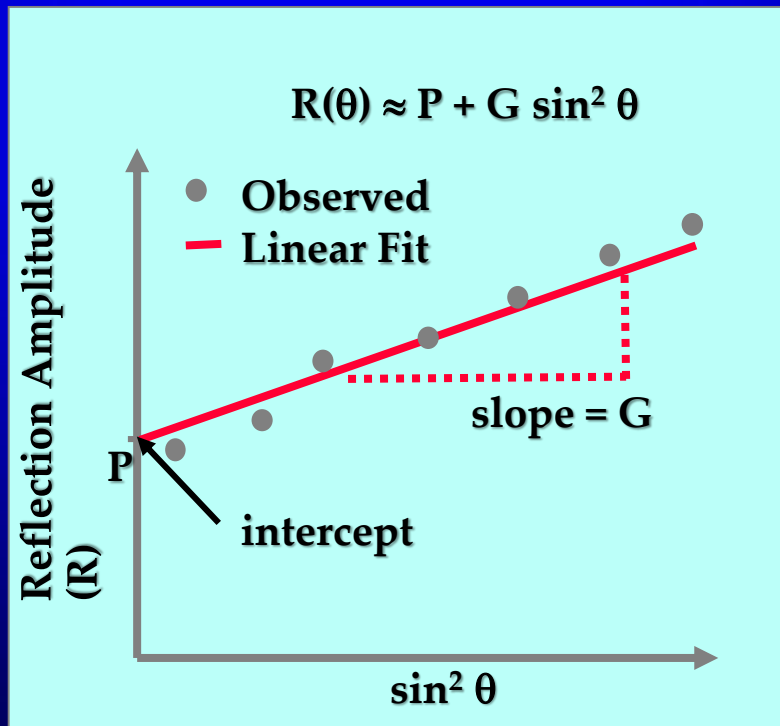
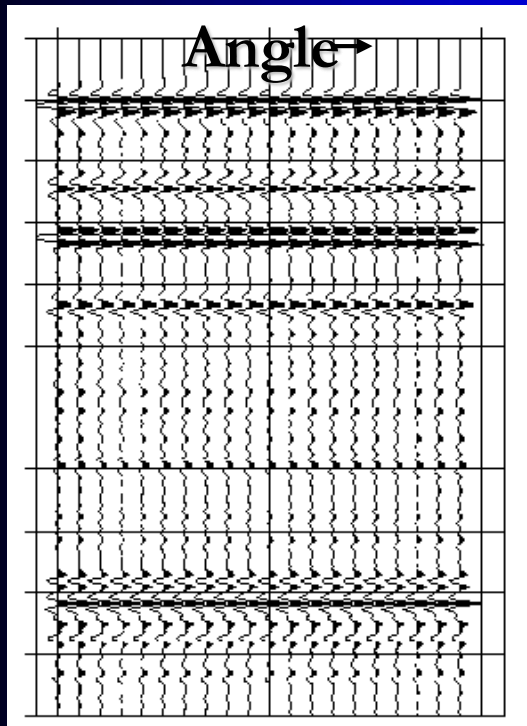
Intercept A = the P-wave reflection amplitude.

Gradient B = the P-wave reflection amplitude minus twice the S-wave reflection amplitude.



AVO

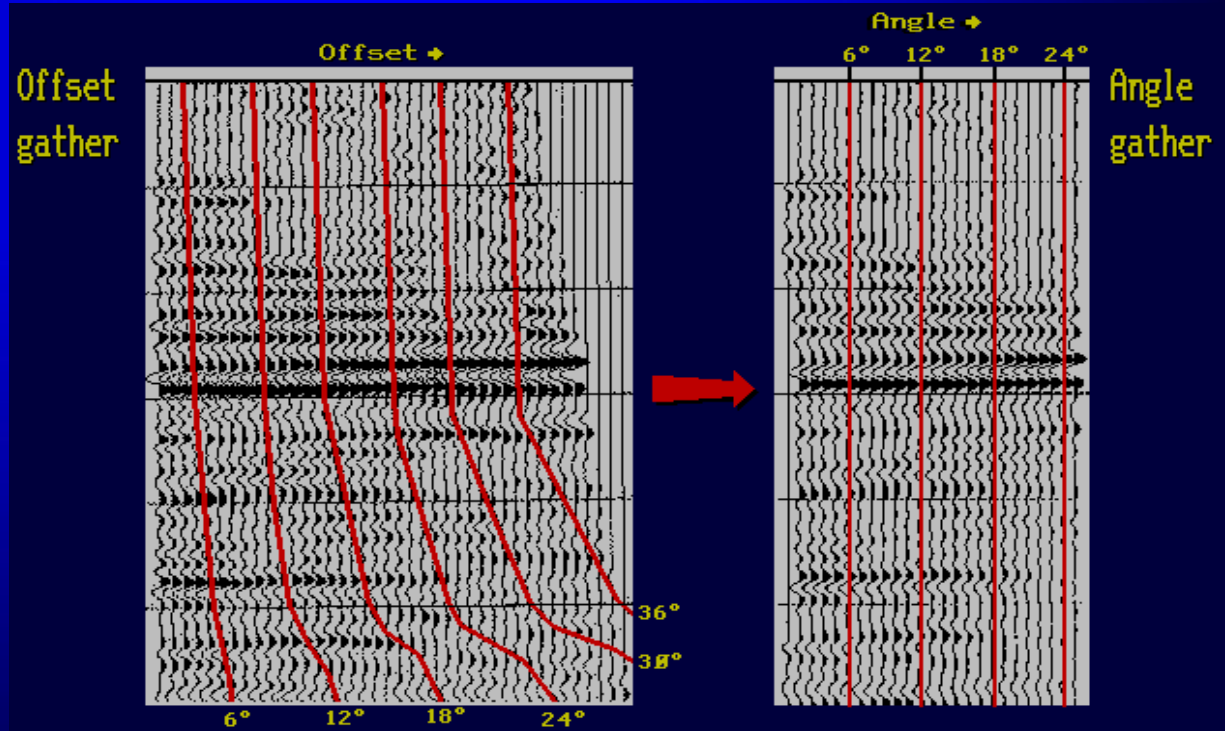
AVO Attributes



AVO

AVO Attributes

Common Angle of incidence calculated from smoothed stacking velocities

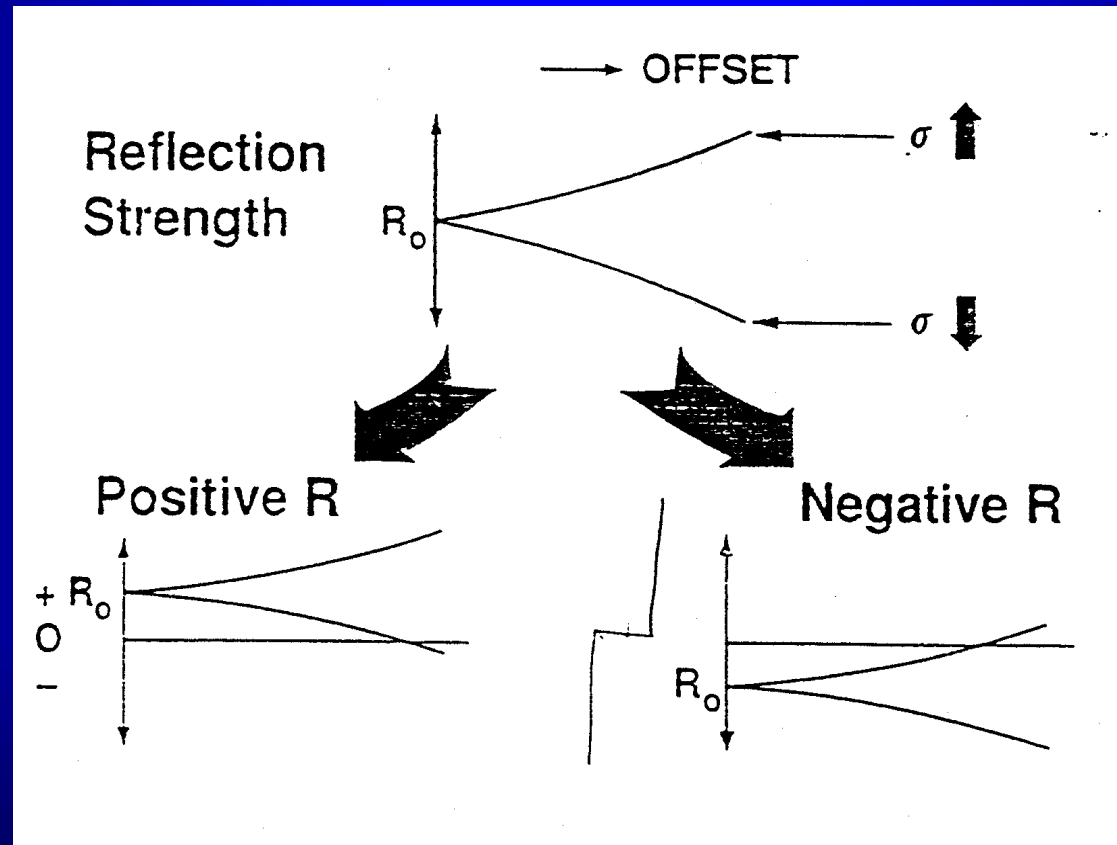


AVO

AVO Attributes

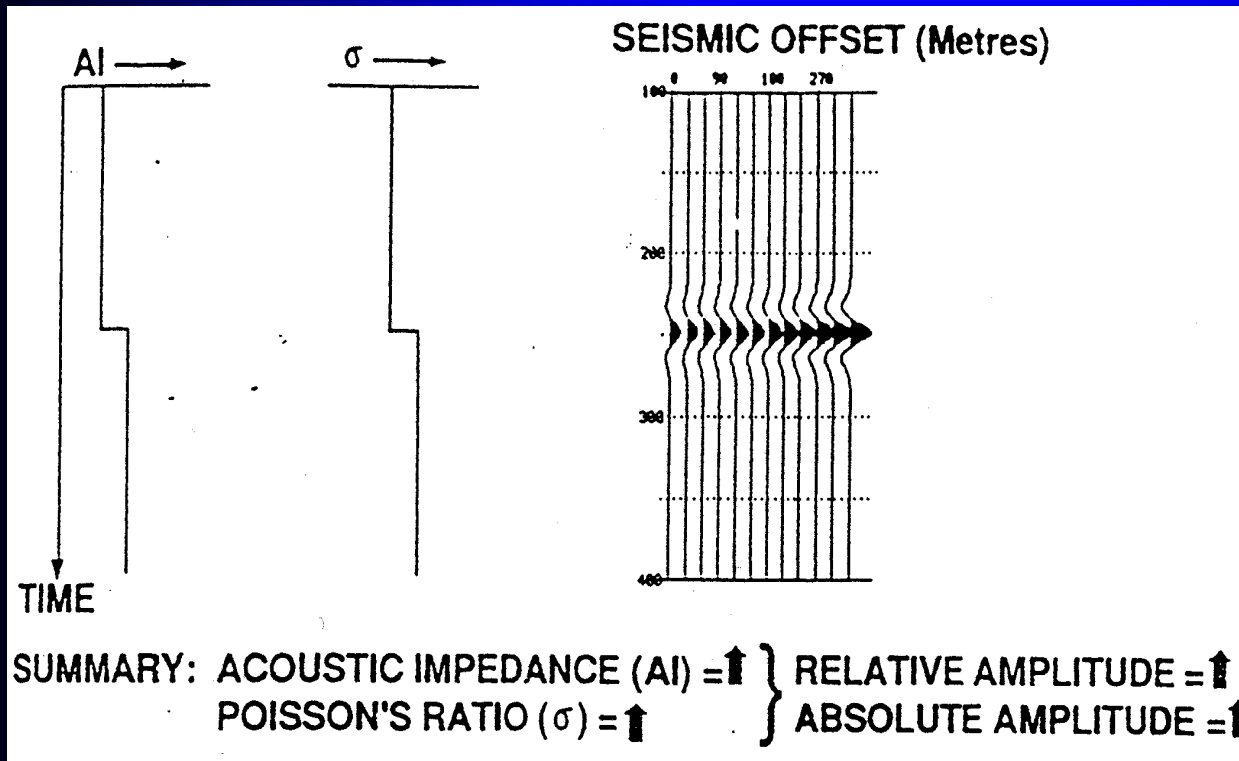
- When we introduce gas into a sandstone, VP decreases whereas VS increases slightly
- We will see that this decrease in VP/VS ratio causes a change in relative amplitude that will vary with angle of incidence.
- By analyzing this variation in amplitude we will try to extract some lithological information from the data
- Poisson's Ratio is a useful number to know as it may be a direct hydrocarbon indicator (DHI)
- S-Waves do not travel in water – they are converted back to P-Waves at the water boundary
- S-waves are less affected by gas than P-waves

Intuitive Development of the AVO Response



The summary of AVO effects due to Poisson's Ratio and AI changes (Russel, 1998)

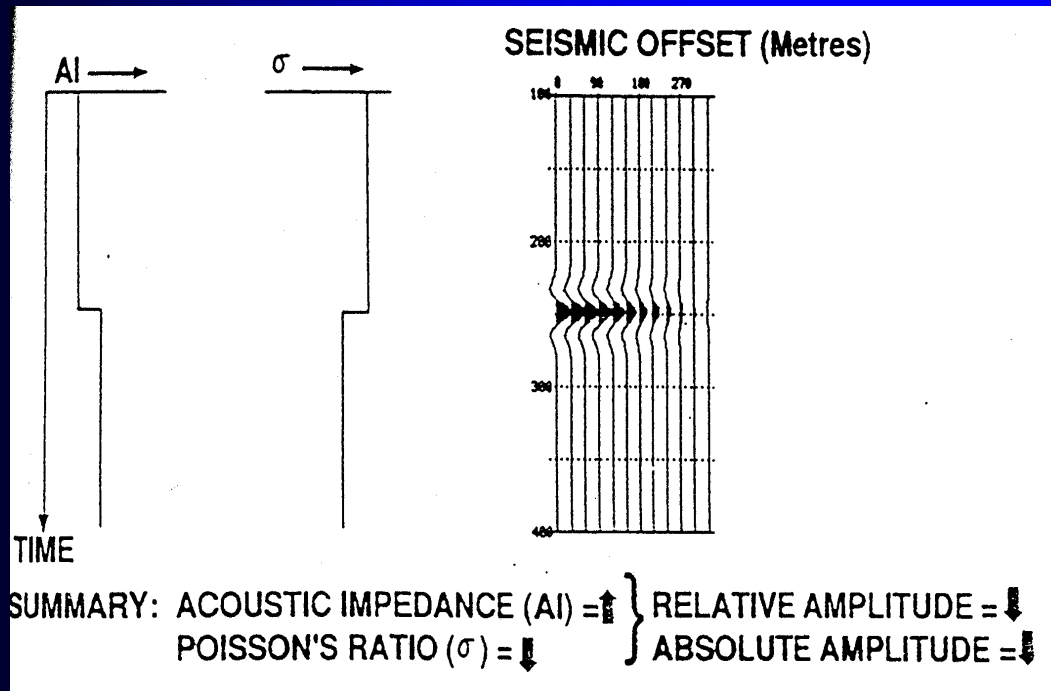
Intuitive Development of the AVO Response



AVO model showing the effect of increasing Poisson's Ratio and AI (Russel, 1998)

If we consider the sign of the reflection coefficient (i.e. the direction of change of acoustic impedance) and if we consider the case of a significant change in Poisson's ratio (i.e. in the order of + or - 0.2), the relative change will still be the same, increasing for an increase in Poisson's ratio, and decreasing for a decrease in Poisson's ratio. However, we are more interested in absolute amplitude change than the relative change.

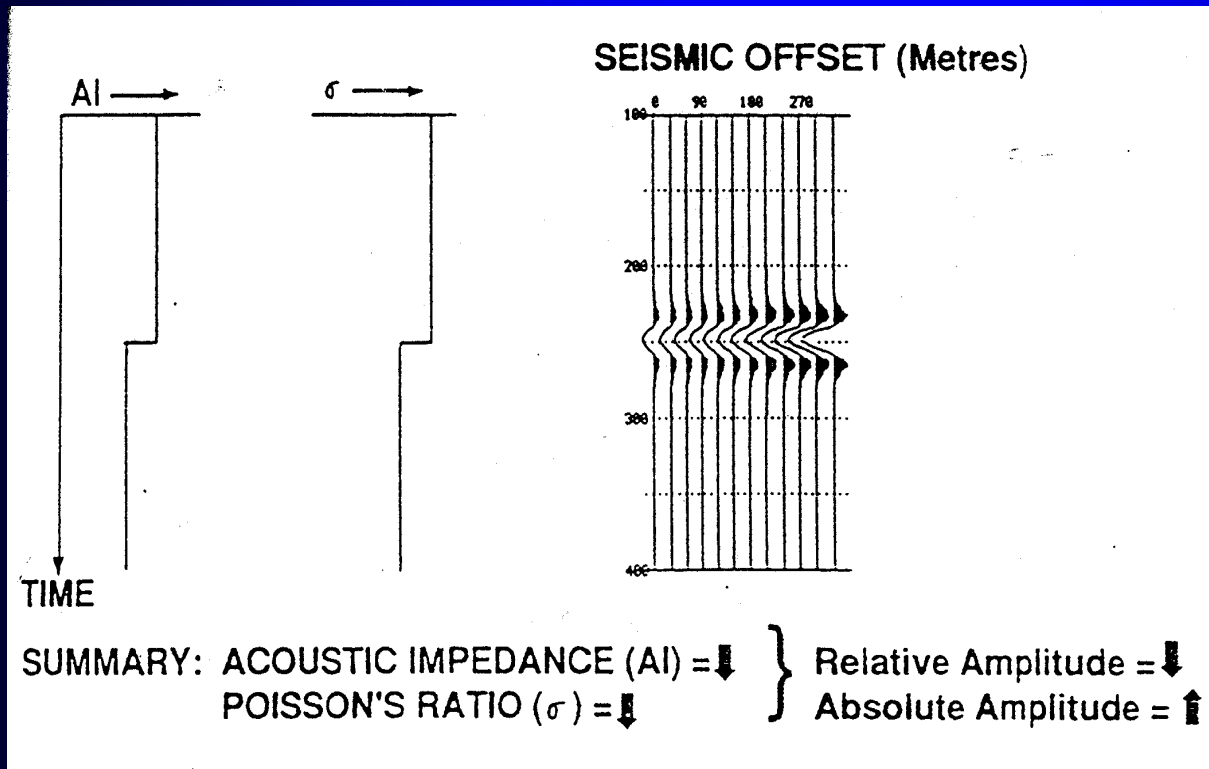
Intuitive Development of the AVO Response



An increase in relative amplitude (AI) with a decrease in Poisson's Ratio, will produce a decrease in absolute amplitude.

AVO model showing the effect of increasing AI and decreasing Poisson's Ratio (Russel, 1998)

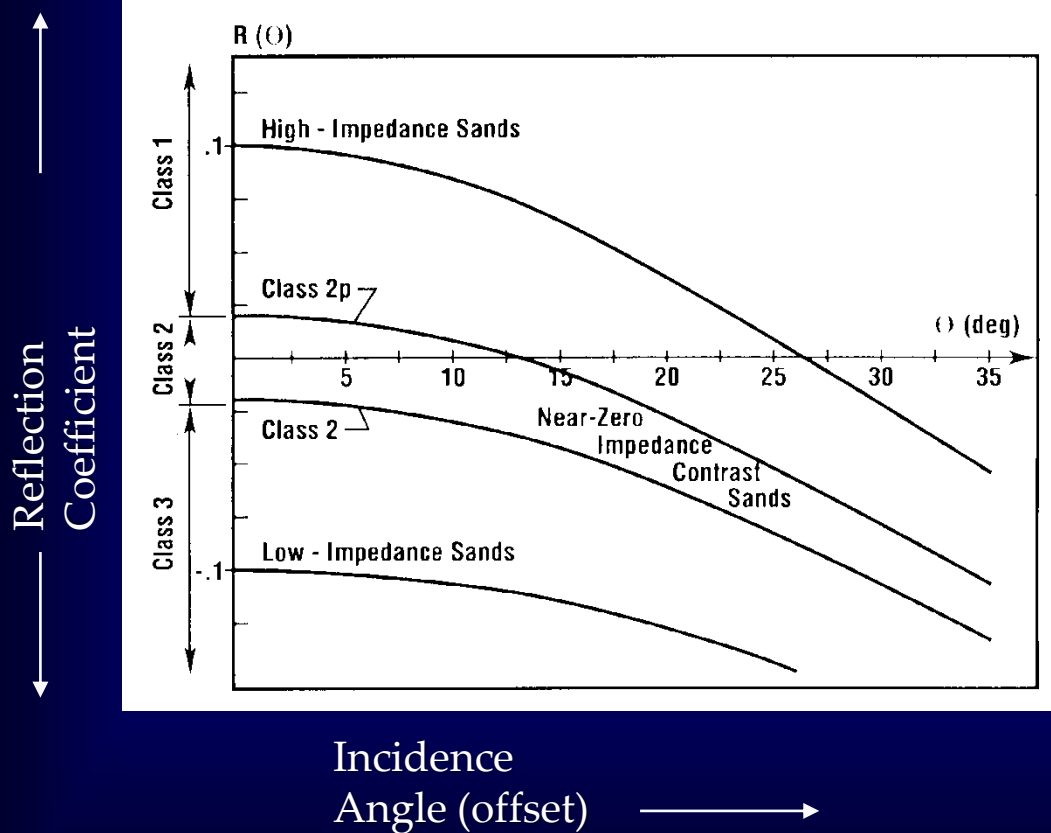
Intuitive Development of the AVO Response



Thus, a relative decrease of Poisson's Ratio for a negative reflection coefficient will produce an increase in absolute amplitude.

AVO model showing decreasing AI and Poisson's Ratio (Russel, 1998)

AVO Classification



Class 1 events are encountered in high impedance reservoirs. The AVO behavior is a peak that dims.

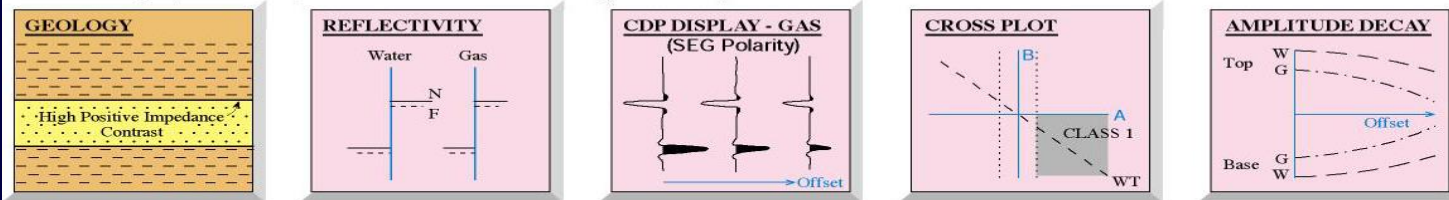
Class 2 events are encountered in near zero impedance reservoirs. The AVO behavior is a weak peak or trough that brightens to a stronger trough at far offsets or incident angles.

Class 3 events are encountered in low impedance reservoirs. The AVO behavior is a trough that brightens at far offsets or incident angles.

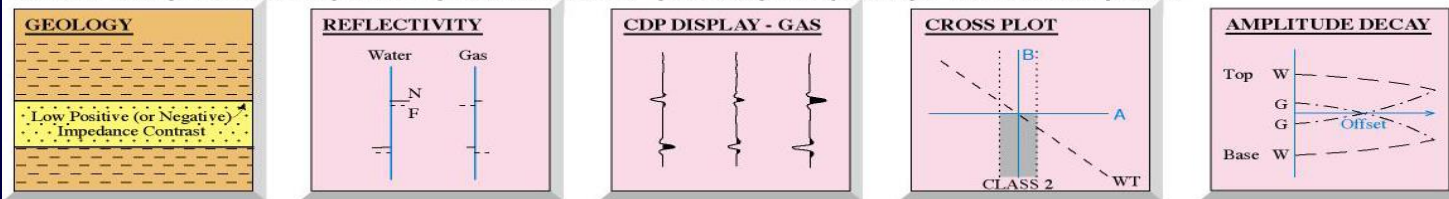
AVO Classification

HYDROCARBON AVO response falls naturally into 4 classes.

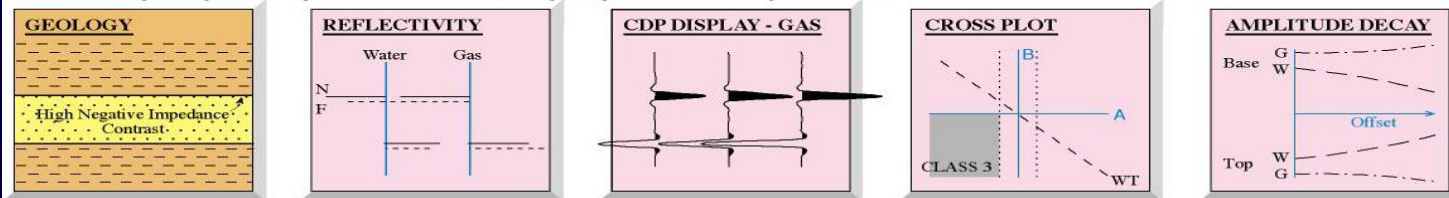
Class 1: High positive impedance contrast - dimming stack amplitude



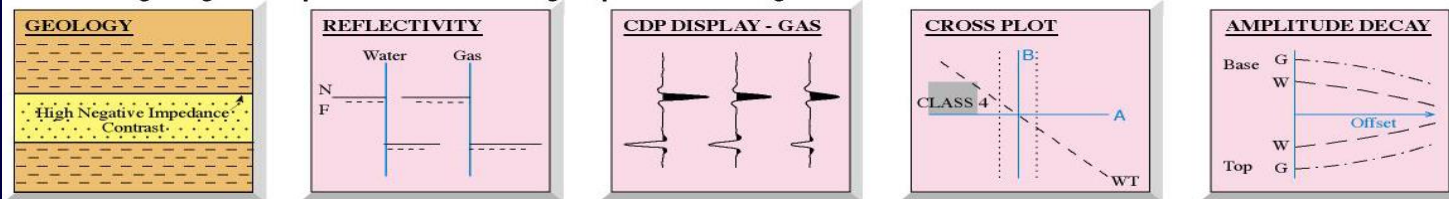
Class 2: Low positive (or negative) impedance contrast - possible polarity change - low stack amplitude



Class 3: High negative impedance contrast. Bright spot - increasing versus offset



Class 4: High negative impedance contrast. Bright spot - decreasing versus offset



AVO Conclusion

- AVO is a measurable physical effect that is due to energy losses caused mainly by P-wave to S-wave conversions at interfaces.
- For normal recording geometries, a plot of reflection amplitude versus the square of the sine of the reflection angle produces an approximate straight line.
- The values of the intercept & gradient of this line provide valuable insight into the velocity, density and Poisson Ratio contrast across that interface.
- Model results, produced from well data, can be used to calibrate these values and identify lithological units within the seismic section.
- Careful processing of the seismic data, designed to eliminate spurious amplitude effects due to the acquisition, is necessary to reveal the sought after effect

4. SEISMIC INVERSION

Terminology and Background

Acoustic Impedance = Velocity X Density

V_p = Velocity of Compressional wave

V_s = Velocity of Shear wave

$V_p/V_s \sim$ Poisson's ratio

-Acoustic Impedance Inversion is a technique for measuring the Impedance of the Earth's sub-surface layers from seismic data

-Using Shear and Compressional Velocities, we can estimate Physical rock properties from seismic data

Multi-Attributes Post-stack limitations

Example: Simple Shale-Sand Model

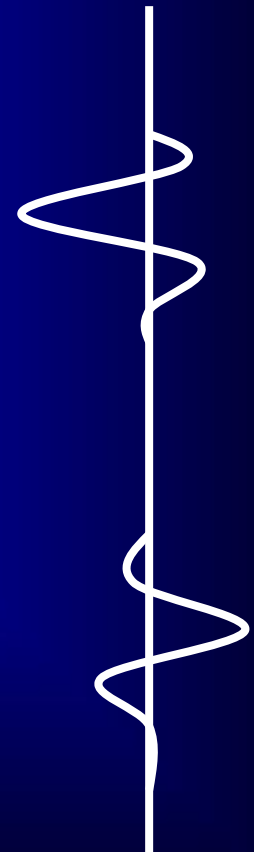
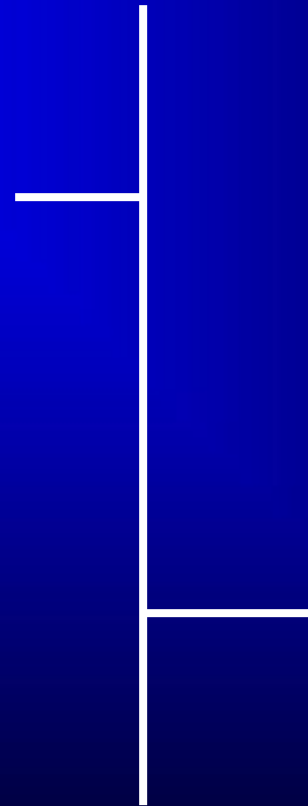
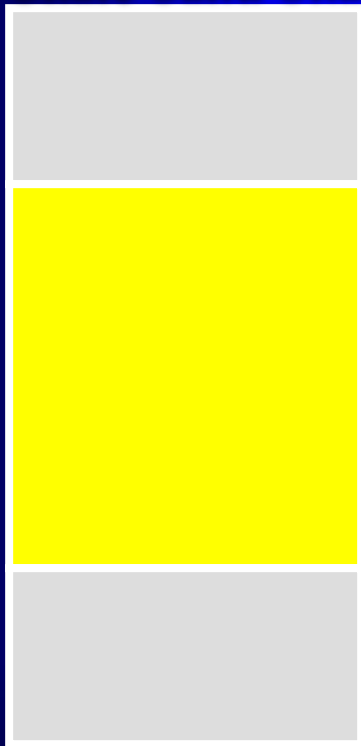
Model:

Acoustic Impedance

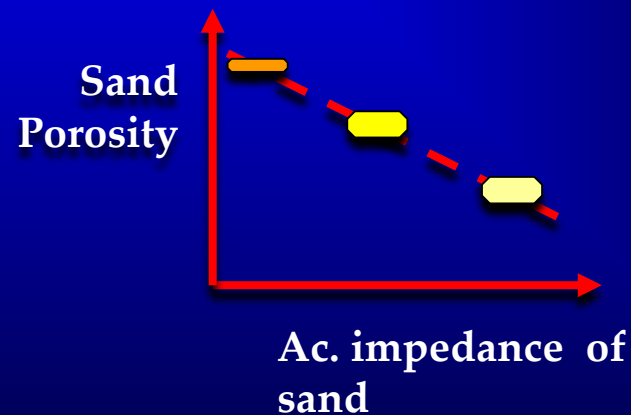
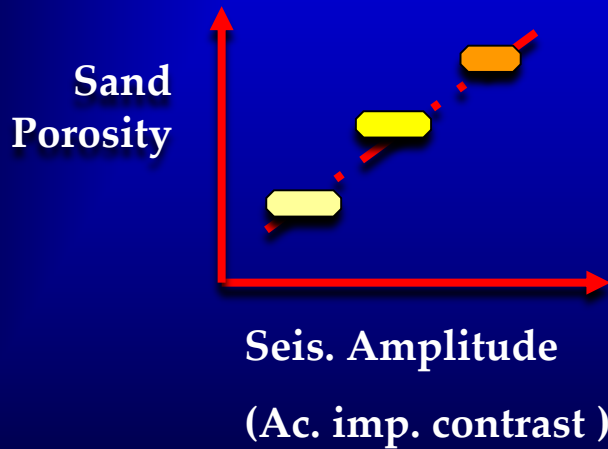
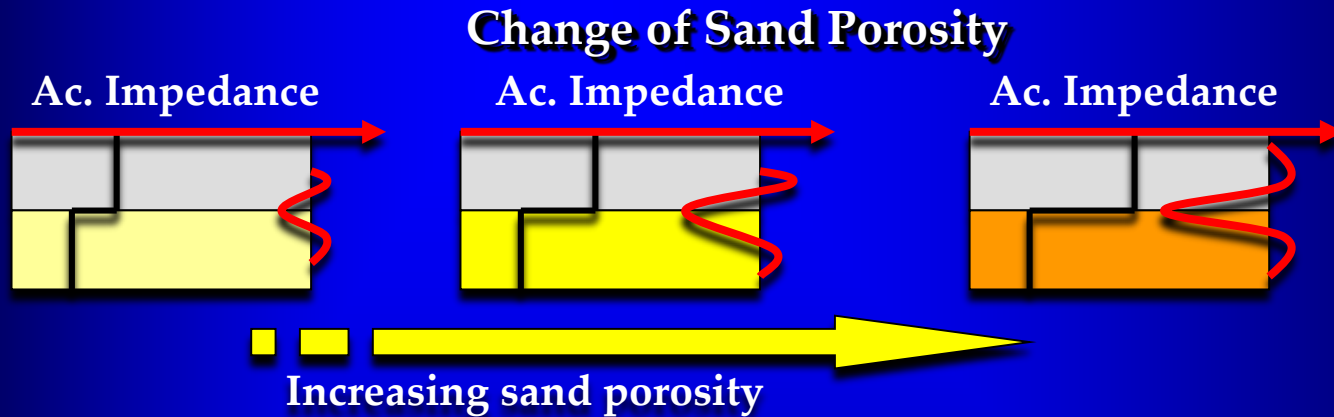
Reflectivity

Seismic

Shale-Sand-Shale

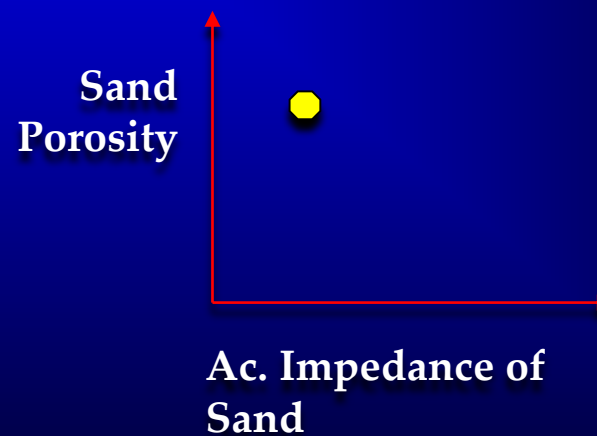
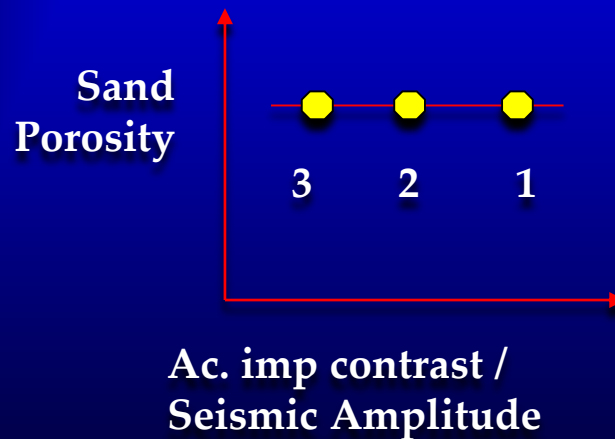
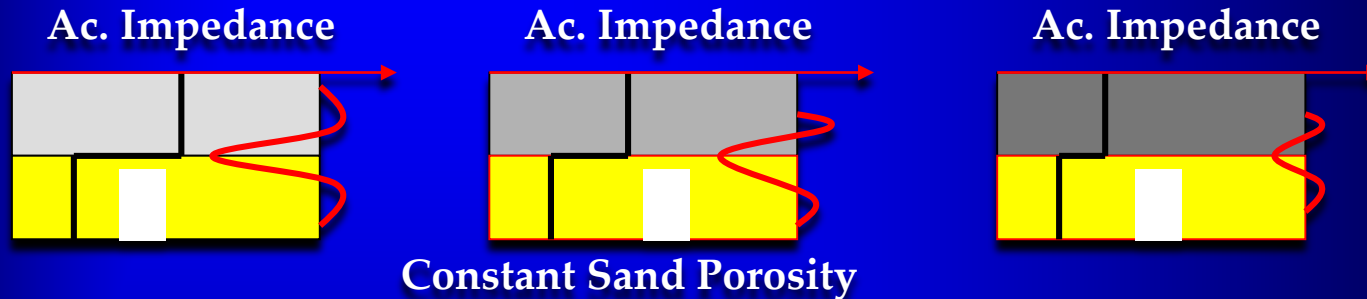


Multi-Attributes Post-stack limitations



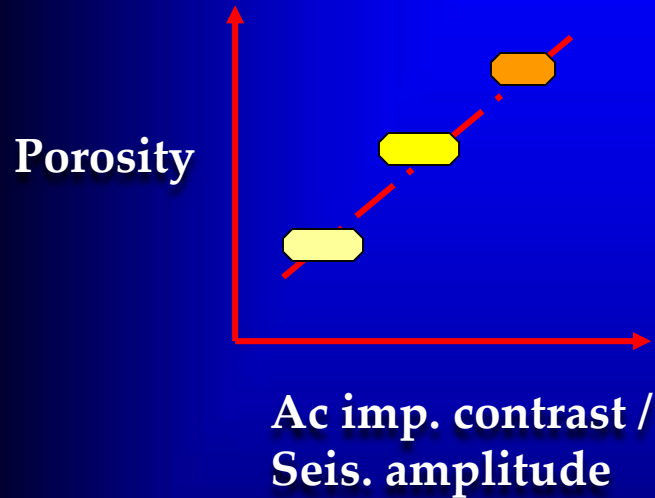
Multi-Attributes Post-stack limitations

Change of Shale Property



Multi-Attributes Post-stack limitations

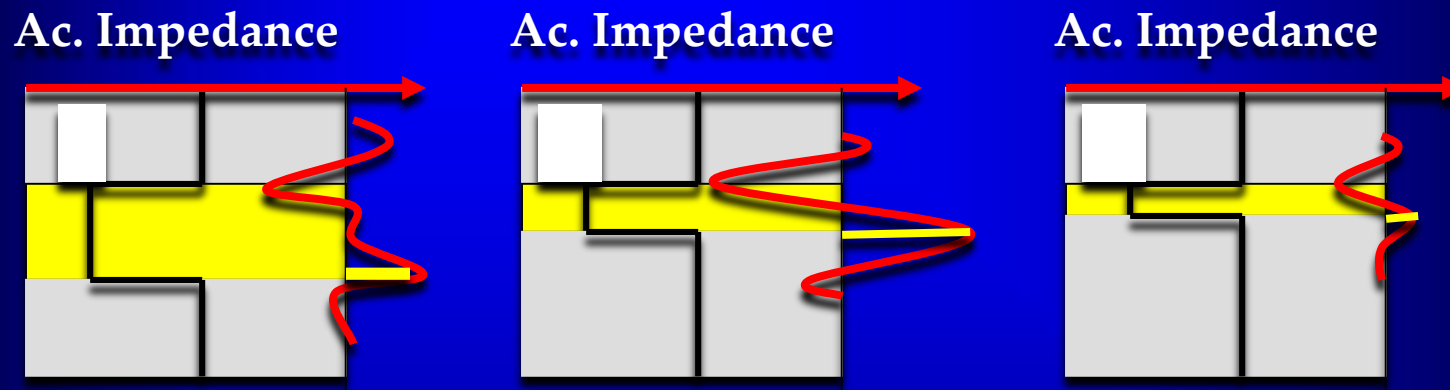
Fundamental Problem



- Only at well positions the relationship between the seismic attribute and the reservoir property (porosity) is derived.
- You assume that this relationship remains valid between the wells.
- However: the acoustic impedance changes may be caused by other parameters or by changes in the neighboring (shale) layers.

Multi-Attributes Post-stack limitations

The Problem of Geometrical Effects for Thin Layers



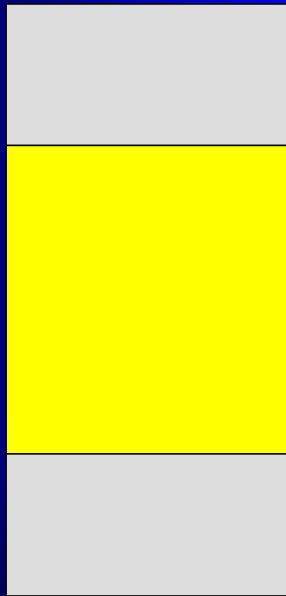
Porosity estimation based on attributes sensitive to tuning effect (seismic amplitudes, instantaneous frequency etc) is questionable.

Multi-Attributes Post-stack limitations

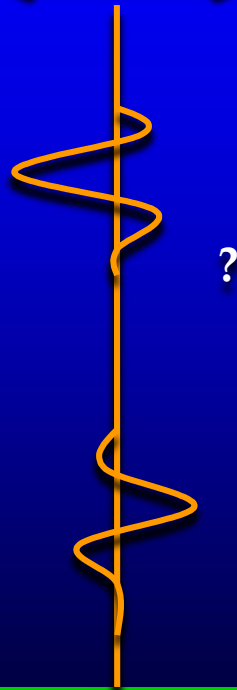
The problem of thick layers Simple Shale-Sand Model

Model:

Shale-Sand-Shale



Seismic



**Seismic delivers no
information about
impedance within the
layer.**

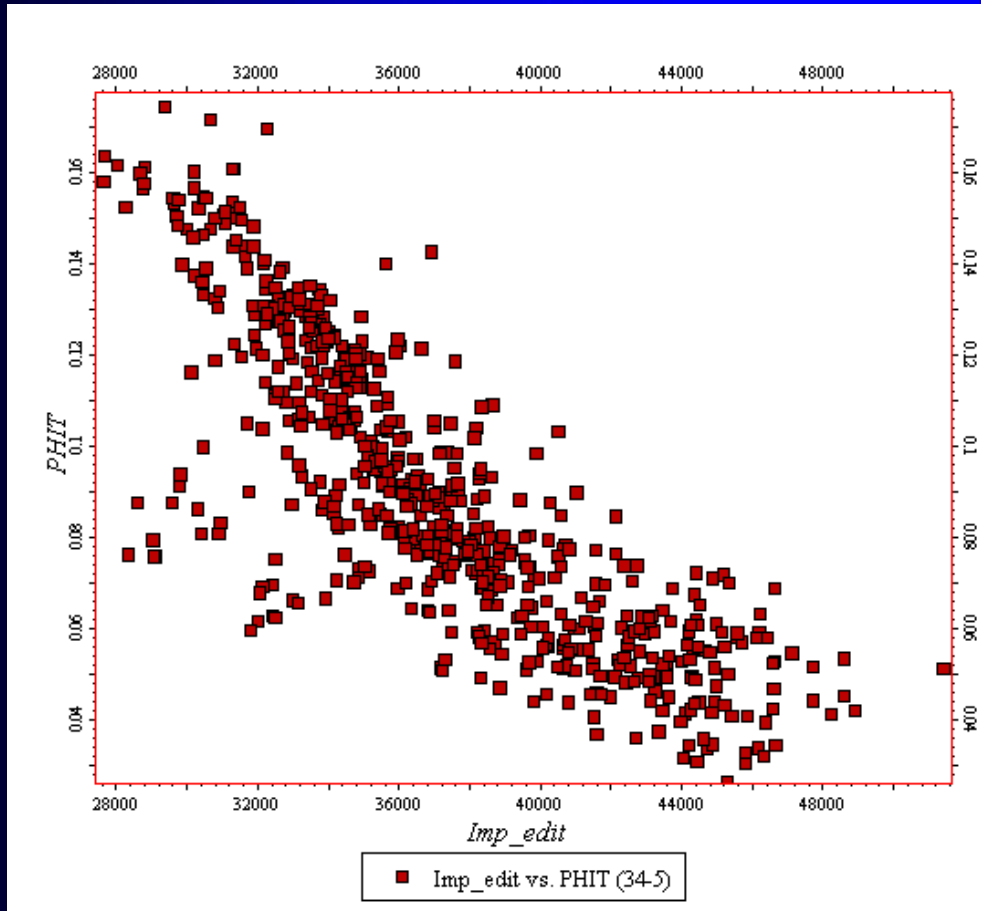
Multi-Attributes Post-stack limitations

Assumptions

- No tuning effect which means either of the following:
 - Reservoir thickness remains constant
 - Reservoir thickness is too big to be influenced by tuning effect
 - Seismic attributes are not sensitive to tuning
- Properties of reservoir are changing, properties of non-reservoir remain constant
- The property we are after has an influence on the seismic

These assumptions need to be carefully checked to trust the derived property maps

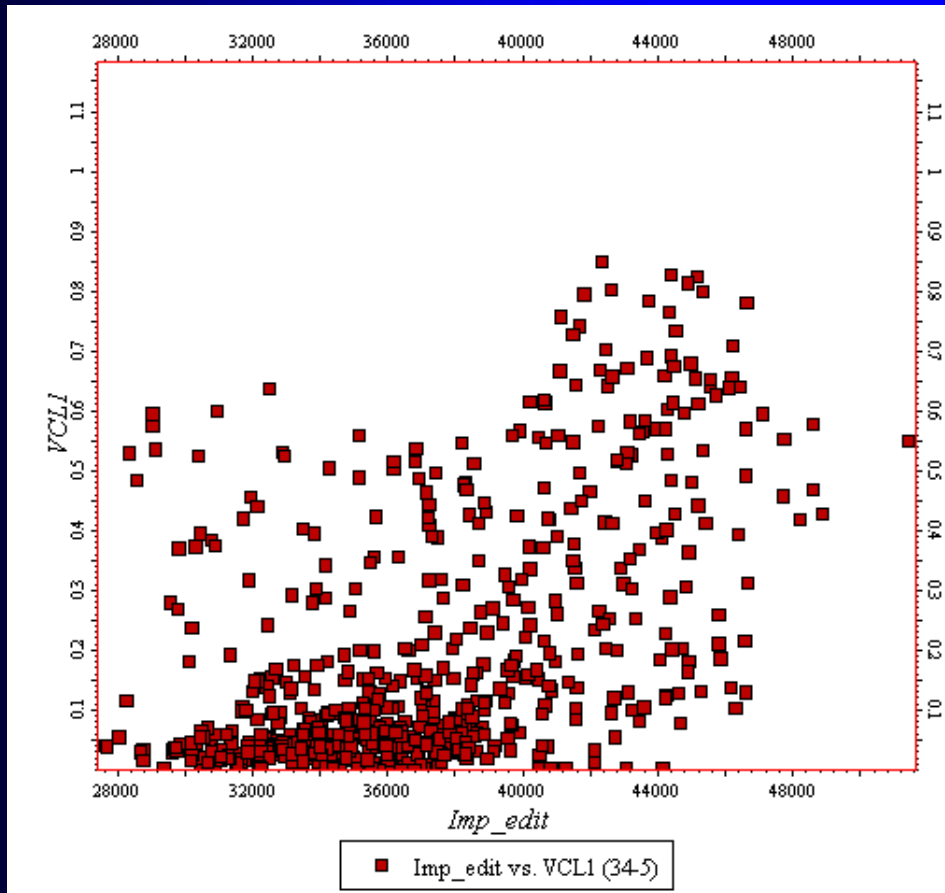
Multi-Attributes Post-stack limitations



For low porosity values the impedance is less sensitive.

Cross Plot Impedance Log vs. Porosity Log

Multi-Attributes Post-stack limitations



No relationship
between
impedance and
shalness.

This seismic
attribute cannot be
used for shale
modeling.

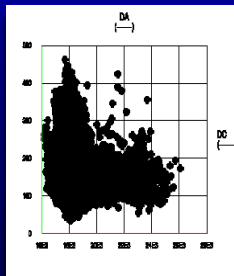
Low Correlation: Cross Plot Impedance Log vs. VCL Log

Multi-Attributes Post-stack limitations

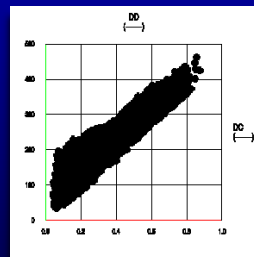
- Seismic attributes should not be sensitive to tuning effect:

Cross plot attributes against reservoir thickness

- Seismic attributes should show a (linear/non-linear) relationship with reservoir property
- In case several attributes pass the tests select those that are linearly independent from each other
- Avoid mixing attributes with opposite signs (negative-positive)
- Avoid mixing attributes with different orders of scale magnitudes



Cross plot attributes against reservoir property



Cross plot against each other, use PCA

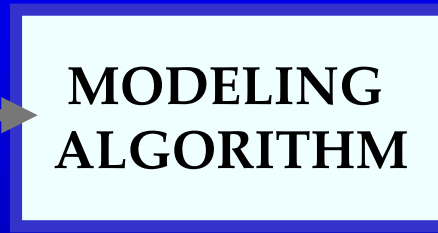
Seismic Inversion

Forward

Input



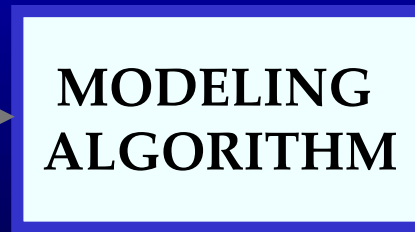
Process



Output

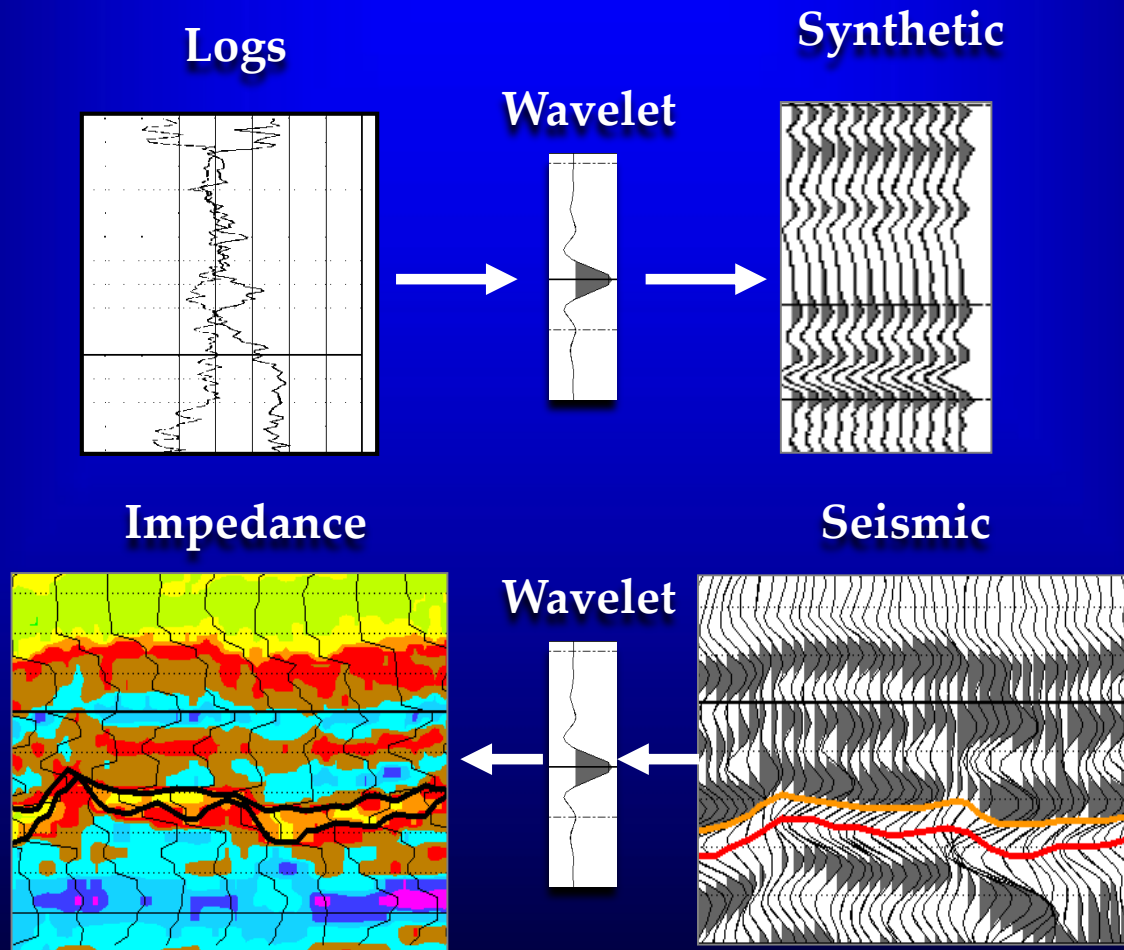


Inverse



Model control

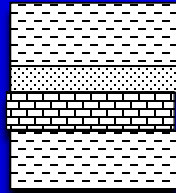
Inversion vs Modeling



What is Inversion

The Making
of Seismic Section

Earth

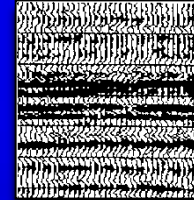


*

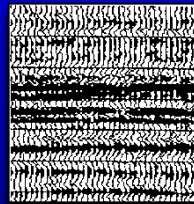
Wavelet



= Seismic Section

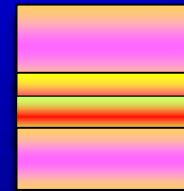


Seismic Section / Wavelet



=

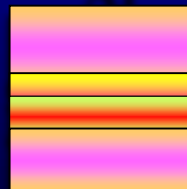
AI



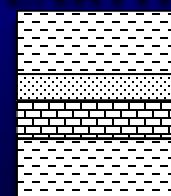
Seismic Inversion
Process

Seismic Inversion
For Reservoir
Characterization

AI



EARTH



Understanding Acoustic Impedance

What is Acoustic Impedance (AI):

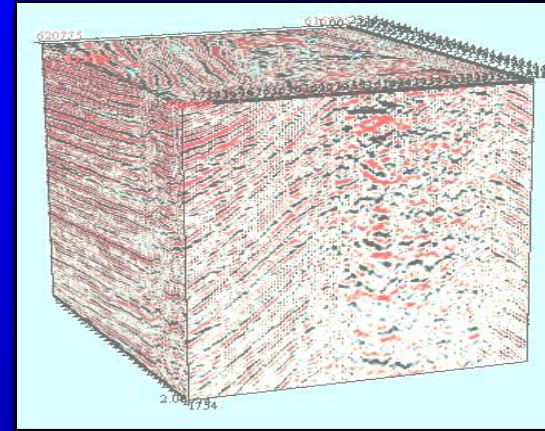
$$AI = \text{Velocity} * \text{Density}$$

PHYSICAL ROCK PROPERTY

Can measure from borehole logs

But can also derive AI everywhere else...

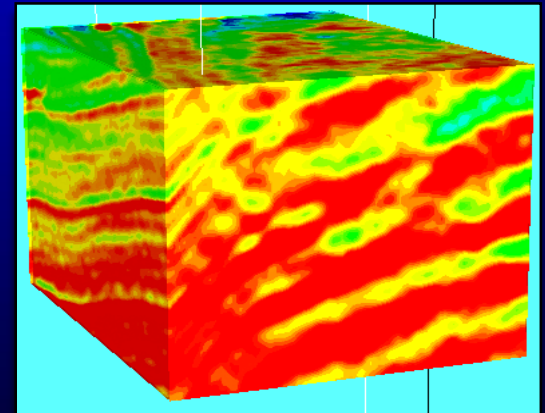
...using seismic inversion!



Why Acoustic Impedance?

Reflection seismic only focuses on interfaces between layers

AI focuses on the layers themselves and what's inside them



Understanding Acoustic Impedance

AI is rock parameter affected by:

- Type of lithology
- Porosity
- Fluids contents
- Depth
- Pressure and temperature

Therefore, AI can be used as an indicator of lithology, porosity, hydrocarbon, lithology mapping, flow unit mapping, and reservoir character quantification.

Naturally, the AI section will give sub-surface geology image more detailed than the conventional seismic section, because the RC on the conventional seismic section will image the layer boundary while the AI will image the layer itself.

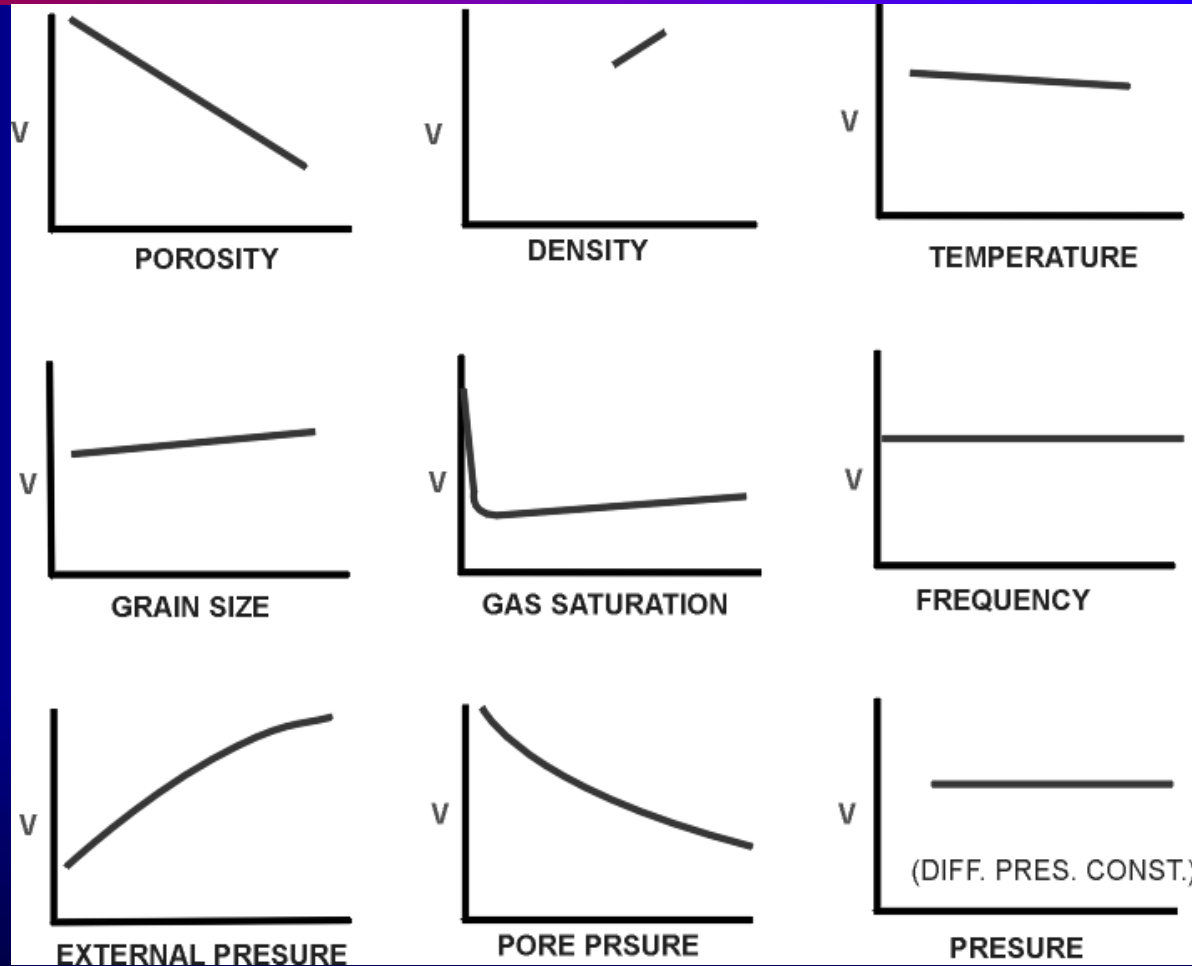
Understanding Acoustic Impedance

The AI will be controlled mostly by the wave velocity.

The porosity and gas content effects are the most effecting factors on P-wave velocity value.

On clastics rock, the porosity depends mostly to differential pressure which is the difference between overburden and interstitial pressures. The porosity decreases when the differential pressure increases in irreversible process.

AI, RC and Reservoir Characterization



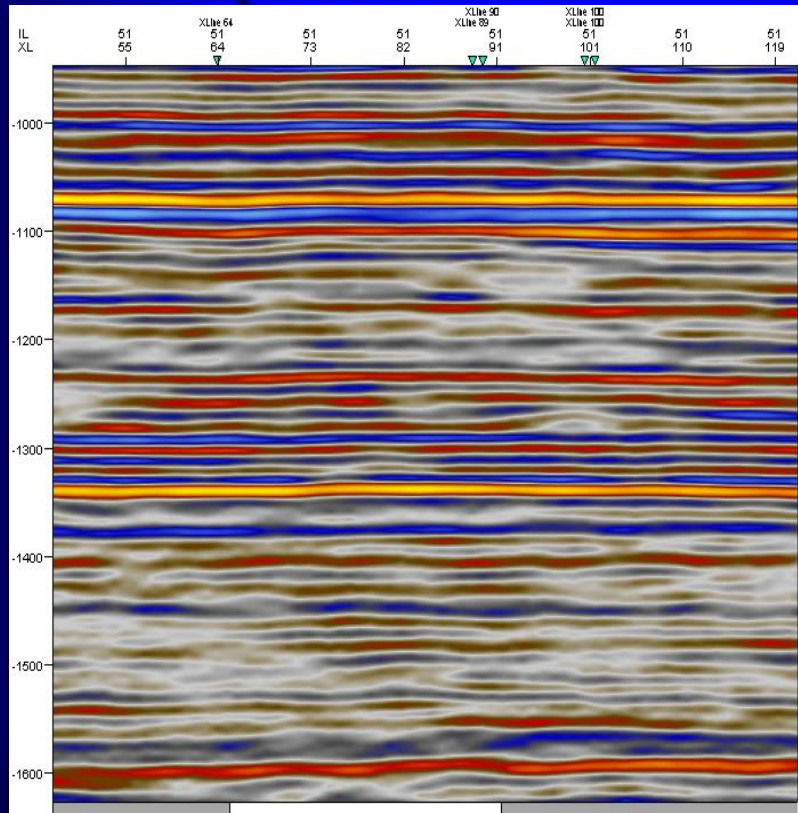
The effects of various factors on seismic wave velocity (Hiltermann, 1977)

Inversion Methods

- **Post-Stack:**
 1. Trace Integration
 2. Colored Inversion
 3. Band-limited
 4. Sparse Spike
 5. Model based
- **Pre-Stack:**
 - AVO Inversion (EI)
- **Neural nets**

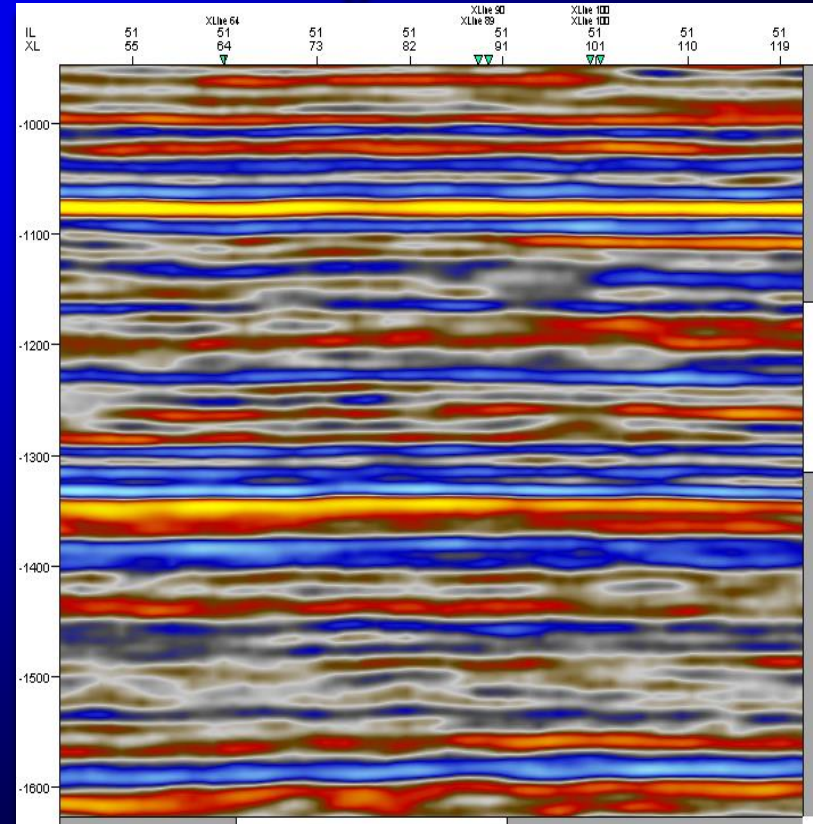
Inversion Methods 1-Trace Integration

Input seismic data



Amplitude

Trace integration inversion

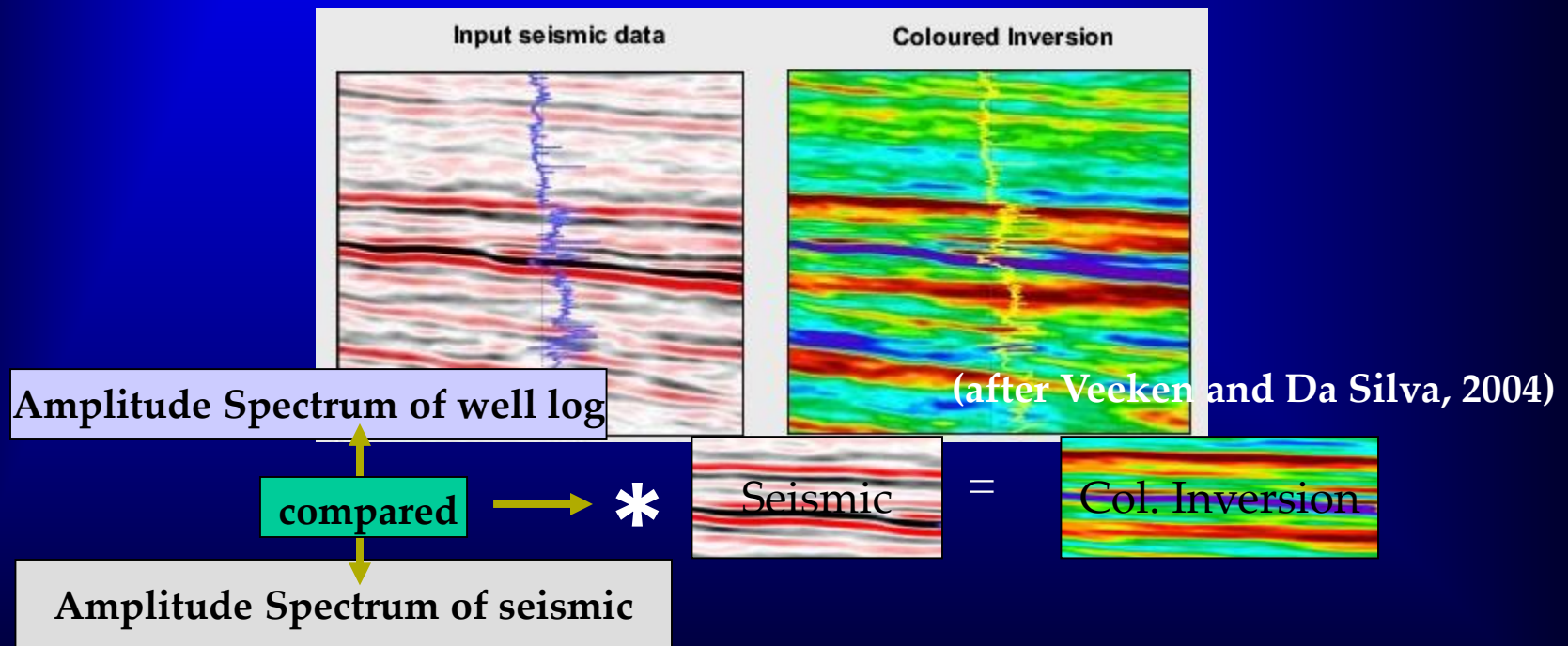


RAI

Inversion Methods 2-Colored Inversion

Input seismic data

Colored inversion



Inversion Methods 3- Band limited

This technique is known as 'bandlimited' inversion because it invert the seismic trace itself.

AI trace result has the same frequency range as the seismic trace.

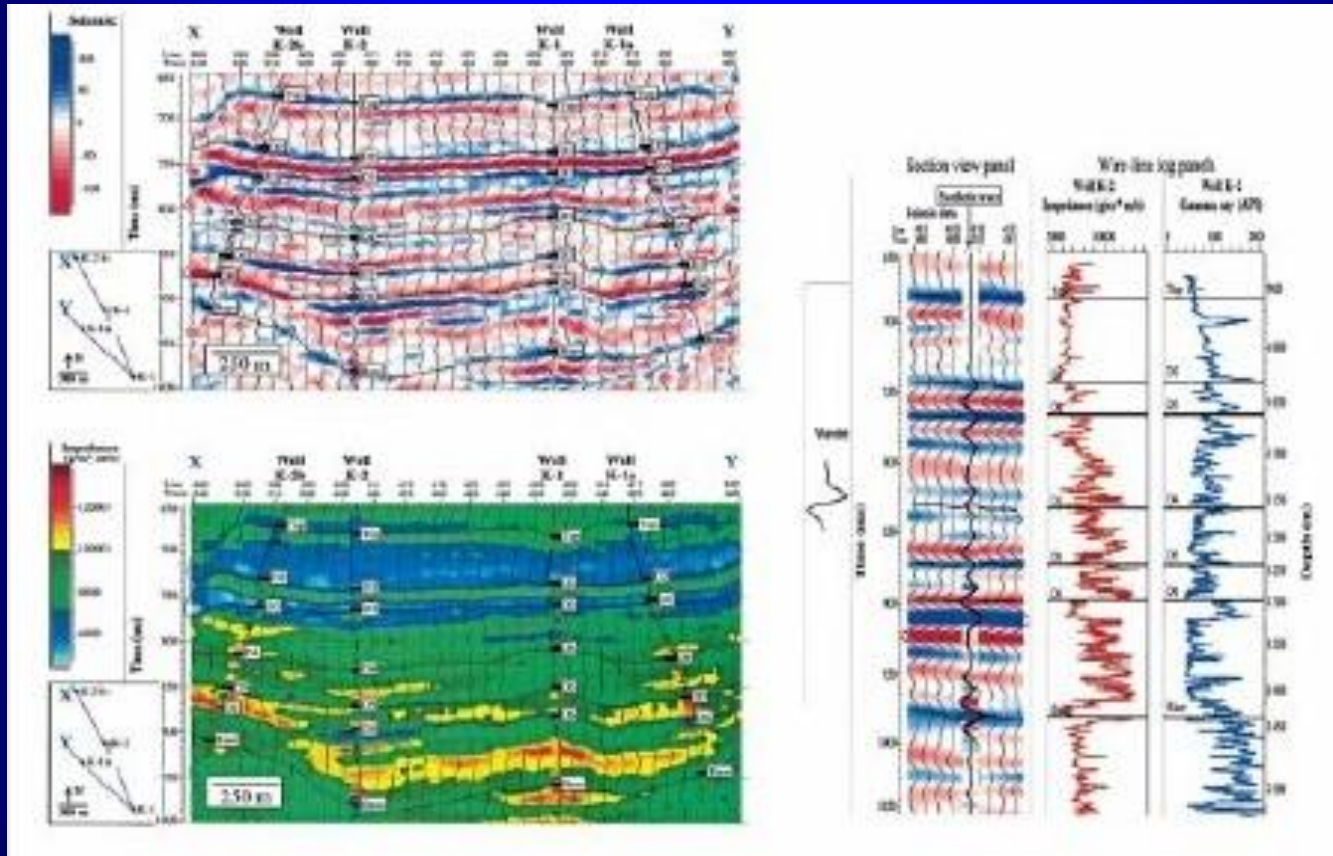
The main weakness of this technique is that it doesn't accommodate the geology control.

It is almost identical to the forward modeling.

The correct wavelet is assumed as zero phase wavelet, so it also will effect the resulted geology model.

Low and high frequency components from earth reflectivity is lost when the reflectivity is convoluted with wavelet.

Inversion Methods 4- Sparse-spike



The sparse-spike method assumes a certain model of the reflectivity (based on spikes) and makes a wavelet estimate based on this model assumption.

Inversion Methods 4- Sparse-spike

The sparse-spike inversion assumes that only the big spike is important.

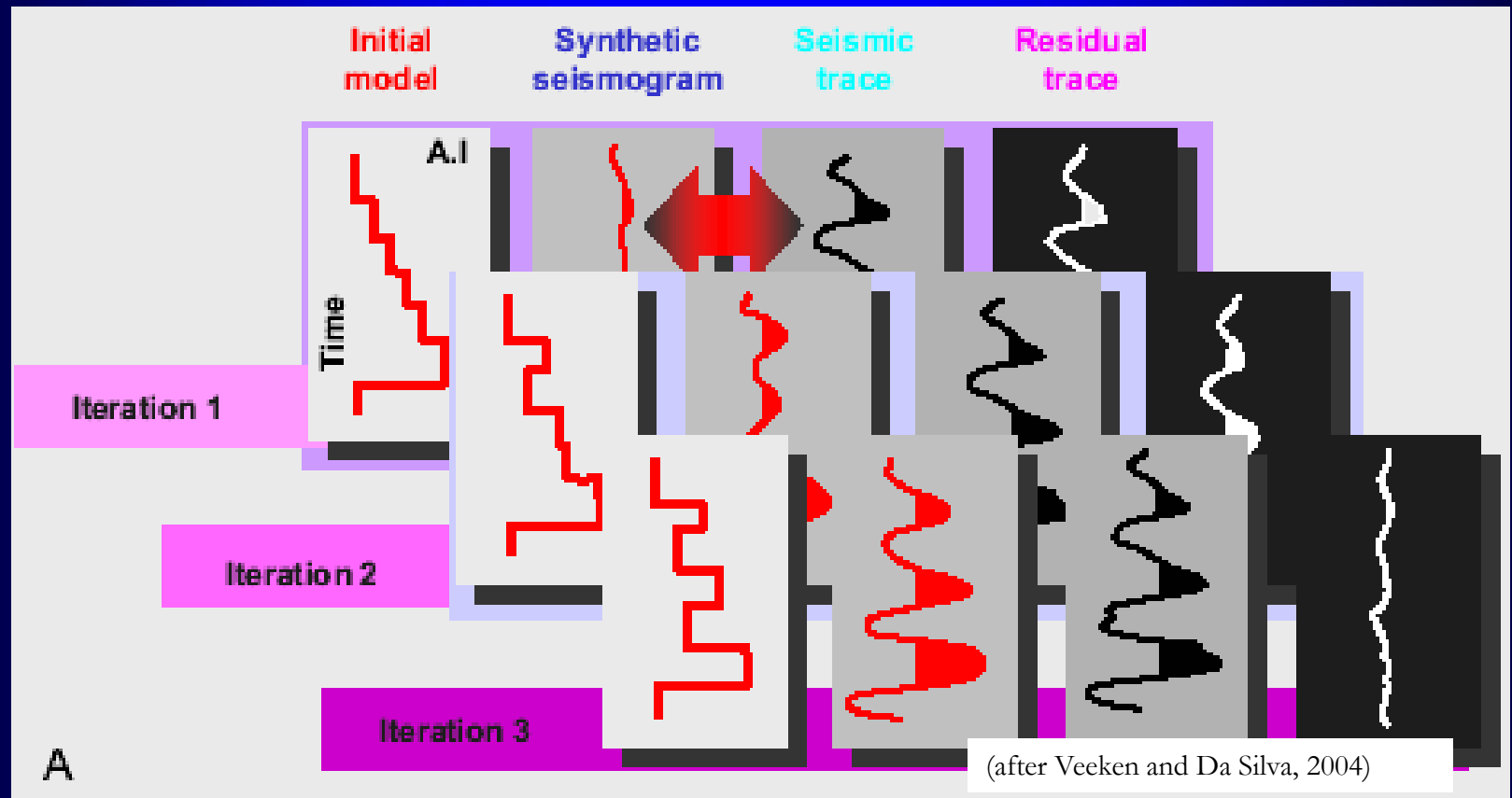
Reflectivity series reconstruct one spike each at a time. The spike are added until the trace is modeled accurately.

The sparse-spike inversion use the same parameter as the model-based inversion with constraint.

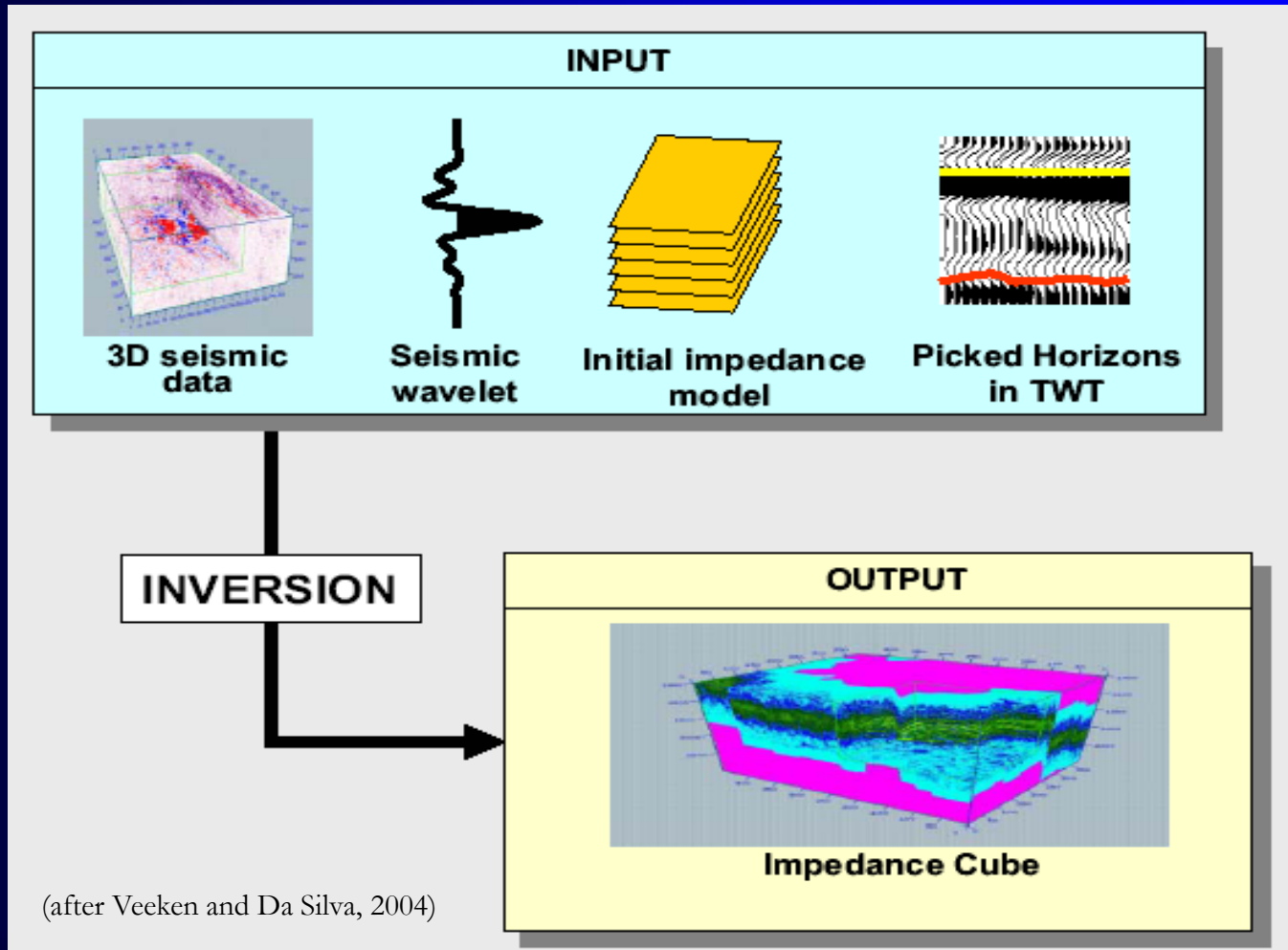
Inversion Methods Model-Based Inversion

The initial AI model and its blocky version is convoluted with the estimated wavelet to recover the synthetic model trace. The seismic synthetic trace is subtracted from real seismic trace to get the trace 'error'. The AI model is perturbed and its thickness iteratively to reduce trace error.

Inversion Methods Model-Based Inversion



Inversion Methods Model- Based Inversion



Sparse-Spike versus Model-based?

Without well data, the inversion will produce relative AI value.

Even the simplest inversion method, it is useful to determine the first exploration well location and predict the drilling problems, such as shallow gas or overpressure zone.

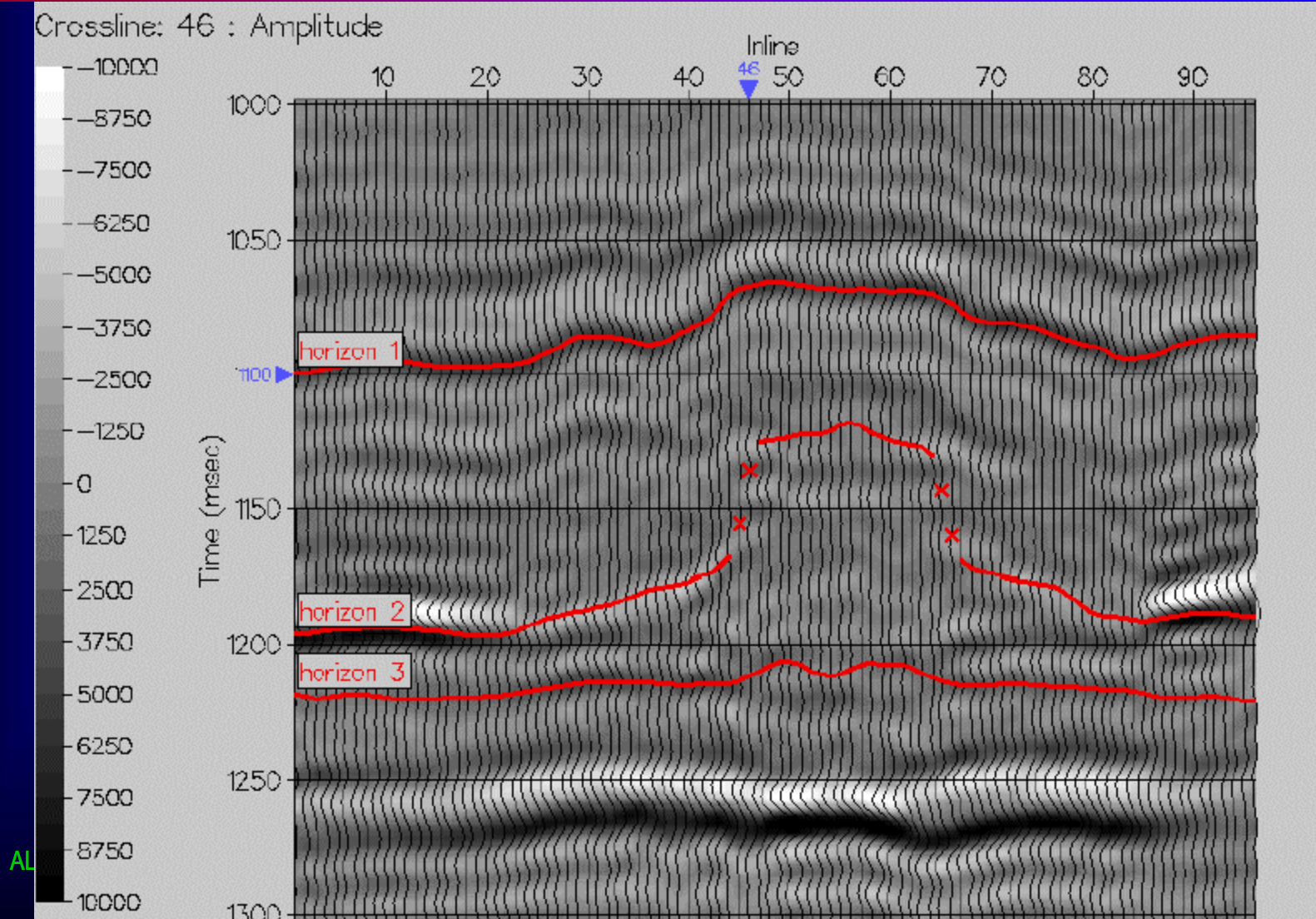
If well data is available, the relative AI can be converted into absolute AI.

Sparse-spike is not recommended for noisy data.

If the seismic data has a good quality and the well data control is sufficient, the selection of model-based method or the sparse-spike method will depend on the reservoir heterogeneity degree.

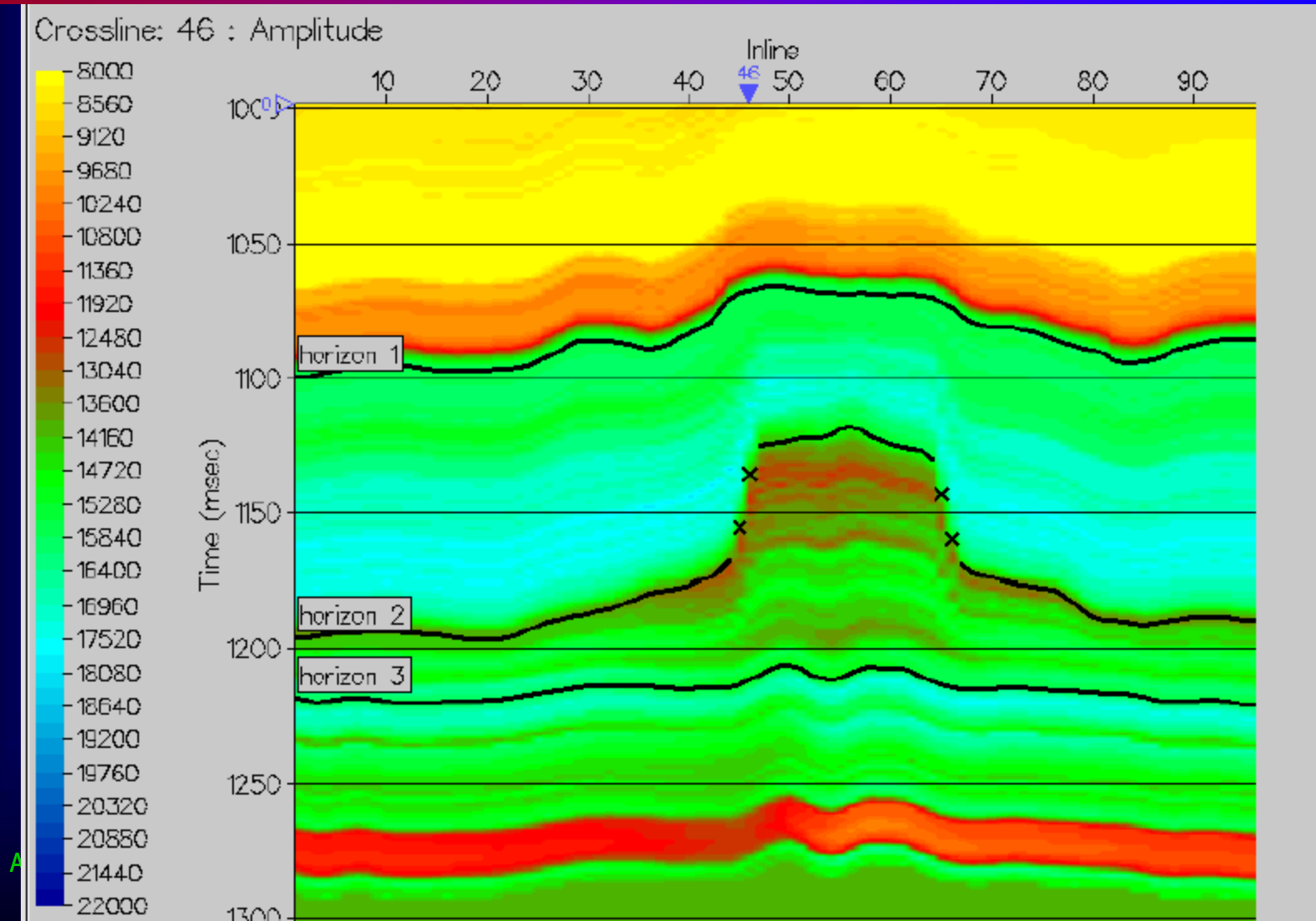
Inversion Methods

Seismic Input Data



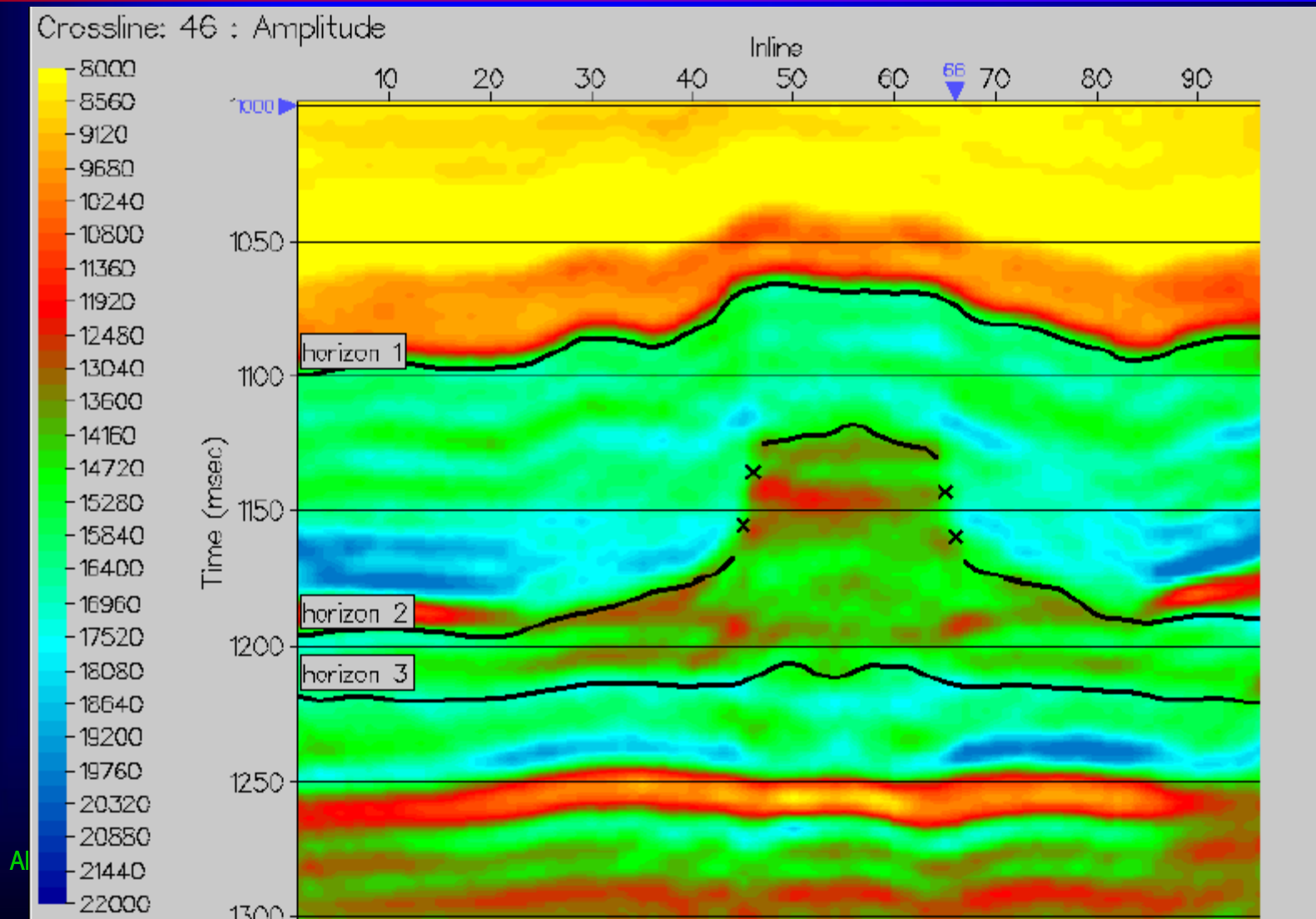
Inversion Methods

Relative Acoustic Impedance by Colored Inversion



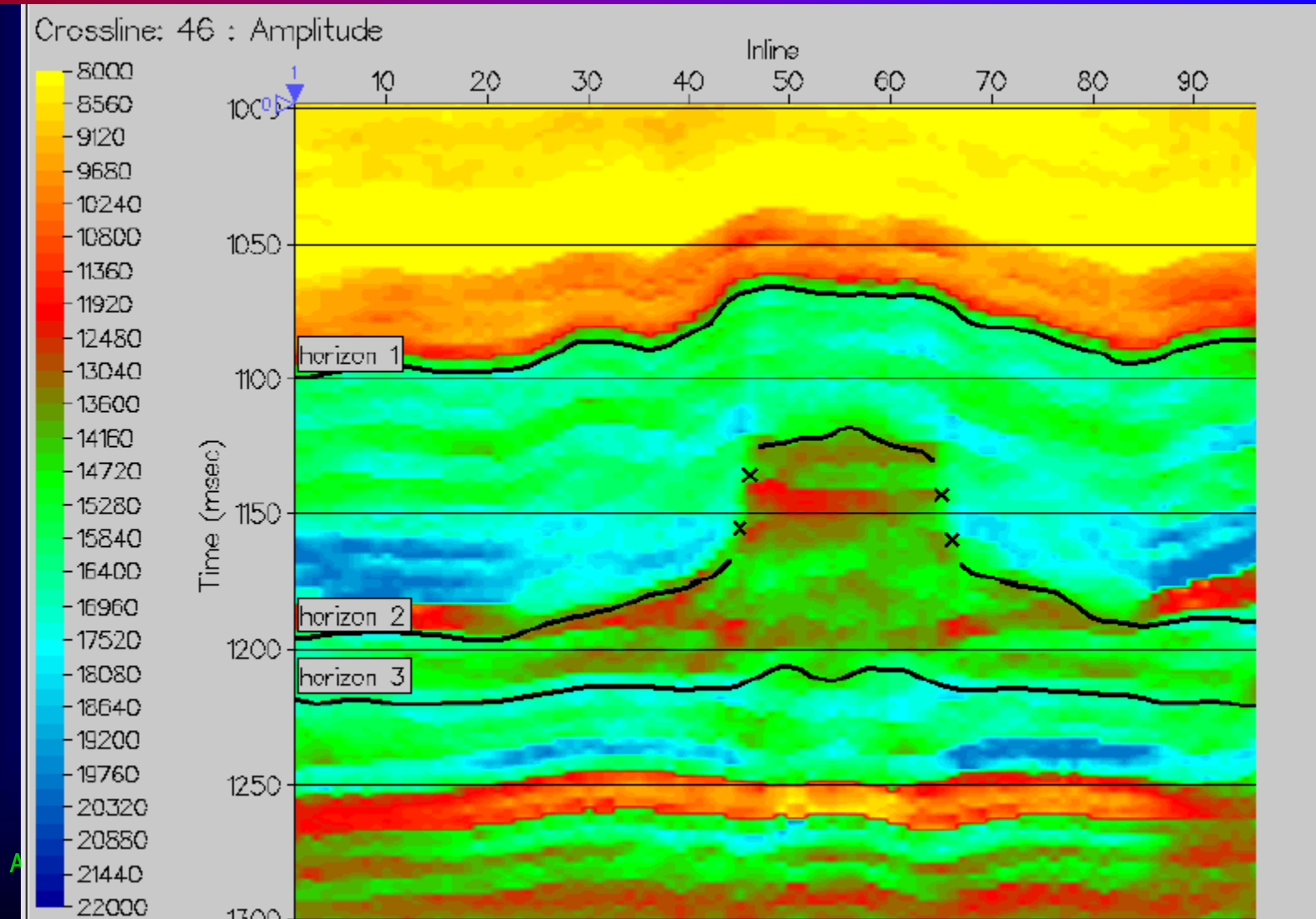
Inversion Methods

Model-Based Acoustic Impedance



Inversion Methods

Discrete Spike Impedance



AVO Inversion

Reflectivity Inversion



Cards and shale have low rigidity, μ (shear rigidity or shear modulus), because they are easy to slide over each other.



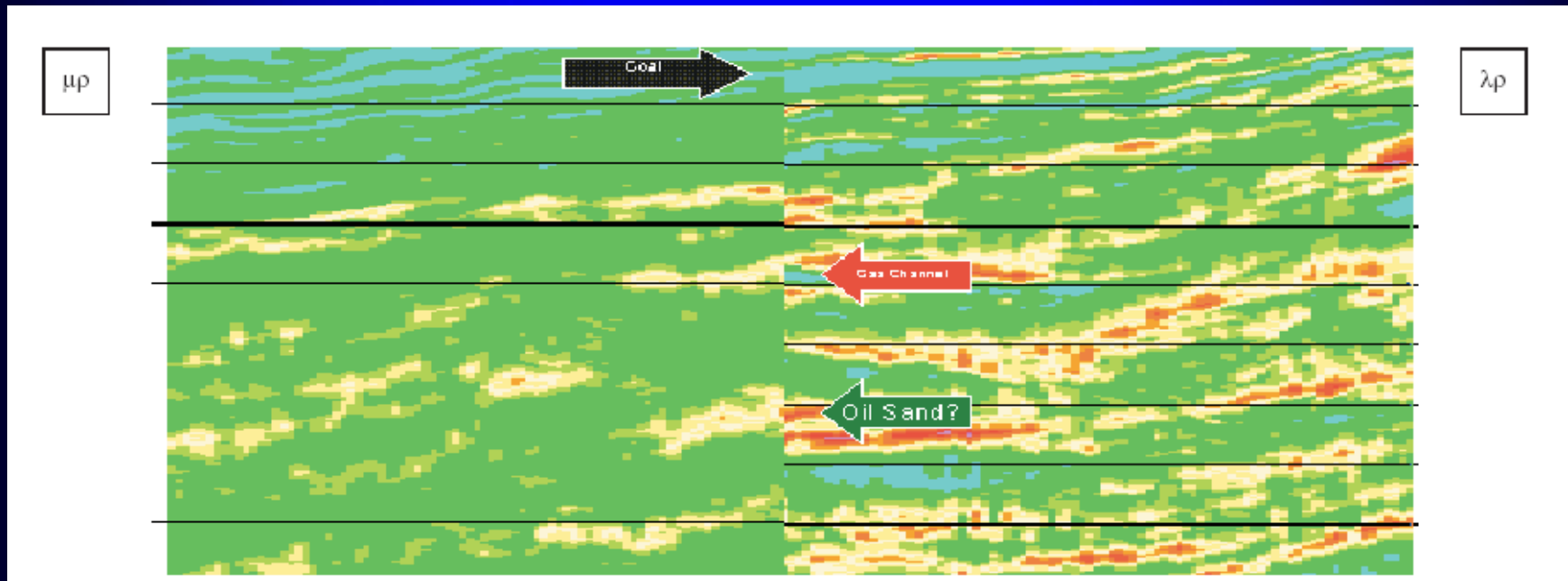
Bricks and limestone have high rigidity because they are difficult to slide over each other. They are also incompressible and so have a high Lamé's modulus, λ .



A sponge and a beach sand have low incompressibility and hence have low Lamé's modulus (bulk modulus).

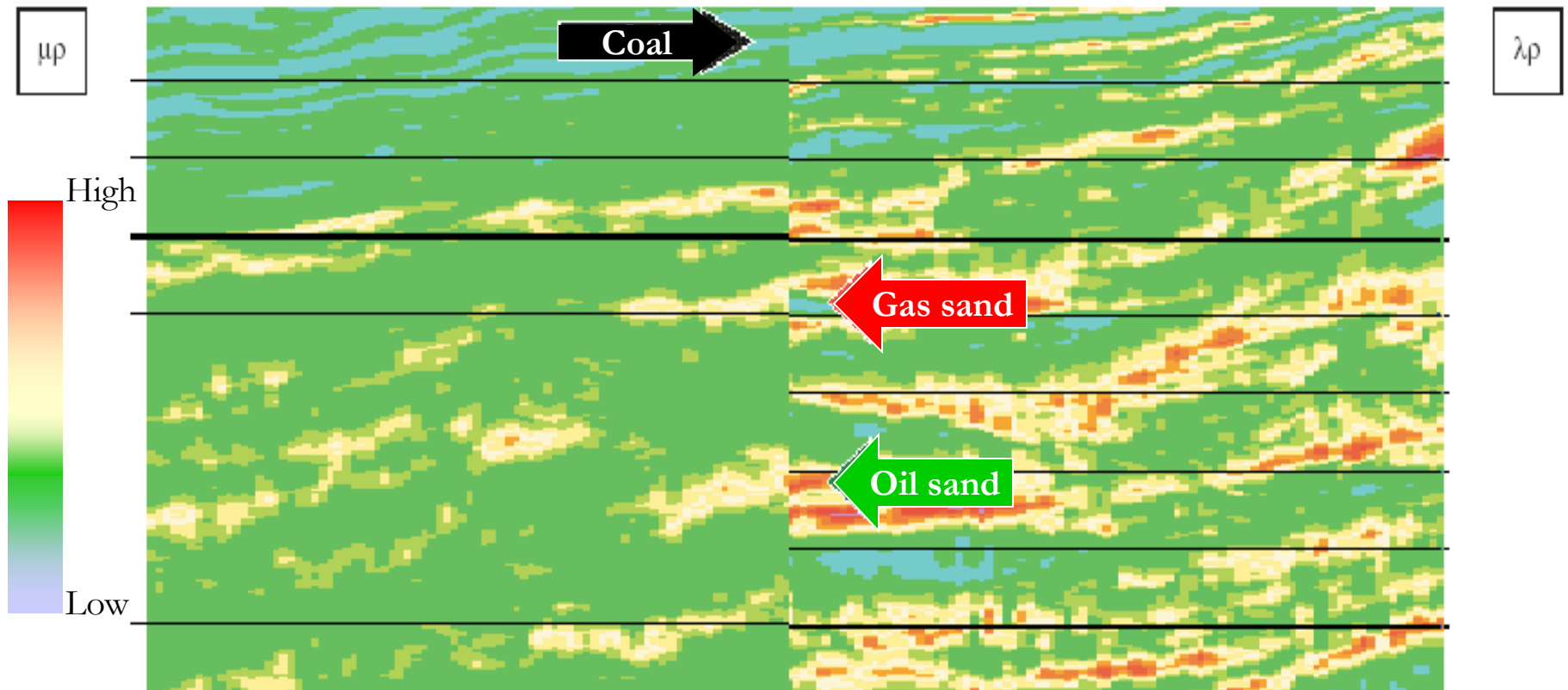
AVO Inversion Attributes

Lambda-Rho and Mu-Rho Inversions



Low values of Lambda-rho and moderate values of Mu-rho can indicate a gas. Low values of Lambda-rho and Mu-rho can indicate coal
(Gray and Andersen, 2001)

Lambda-Rho and Mu-Rho Inversions

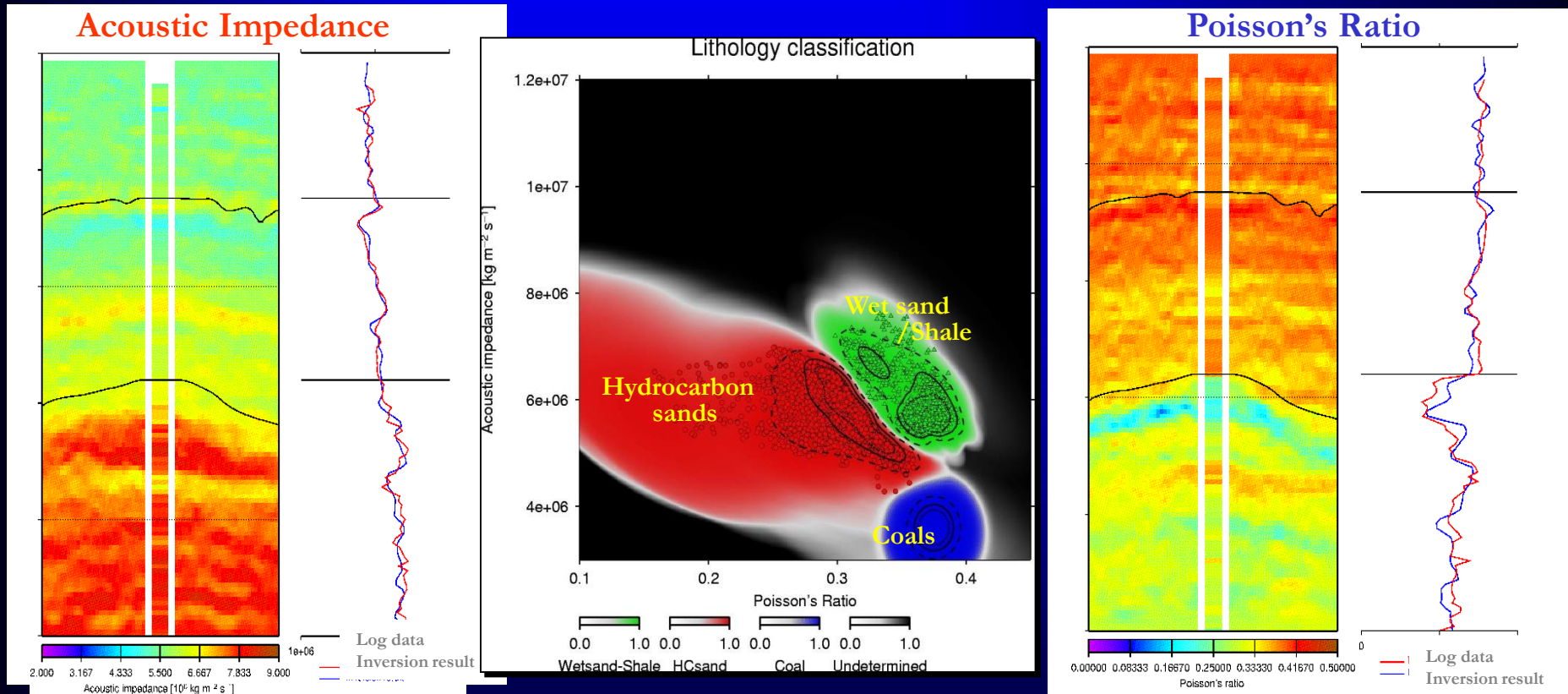


Low values of Lambda-rho and moderate values of Mu-rho can indicate a gas.

Low values of Lambda-rho and Mu-rho can indicate coal

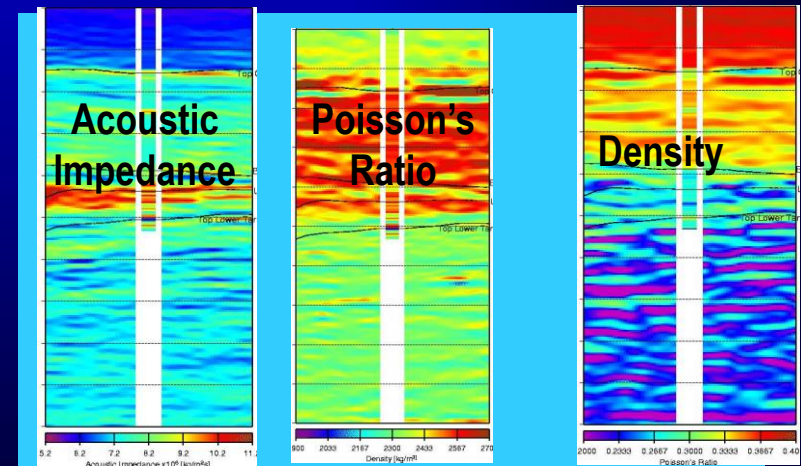
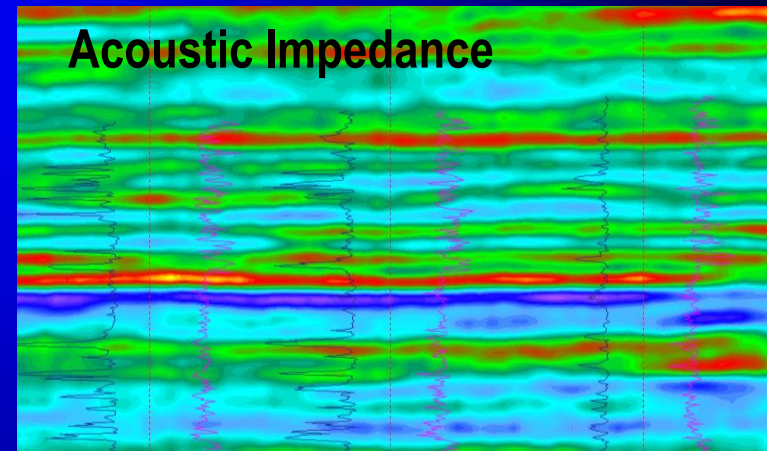
(Gray and Andersen, 2001)

Lithology Classification Using seismic inversion outputs



Inversion Approaches & Outputs

Inversion Method	Outputs	Common Uses
Full Stack	AI	Porosity Lithology Indicator
AVO (Simultaneous)	AI PR Density	Porosity Lithology prediction Fluid Type (gas, oil, water)



Inversion Methodology

- Log Conditioning and analysis
- Well log editing (sonic and density)
 - Petrophysical well log analysis
 - Geophysical well log analysis – Rock Physics modelling
- Seismic Data Preconditioning
 - Low frequency model
 - Wavelet estimation and stacks conditioning
- Inversion - AI, SI, Poisson's Ratio, and Density
- Calibration/Prediction of Reservoir properties

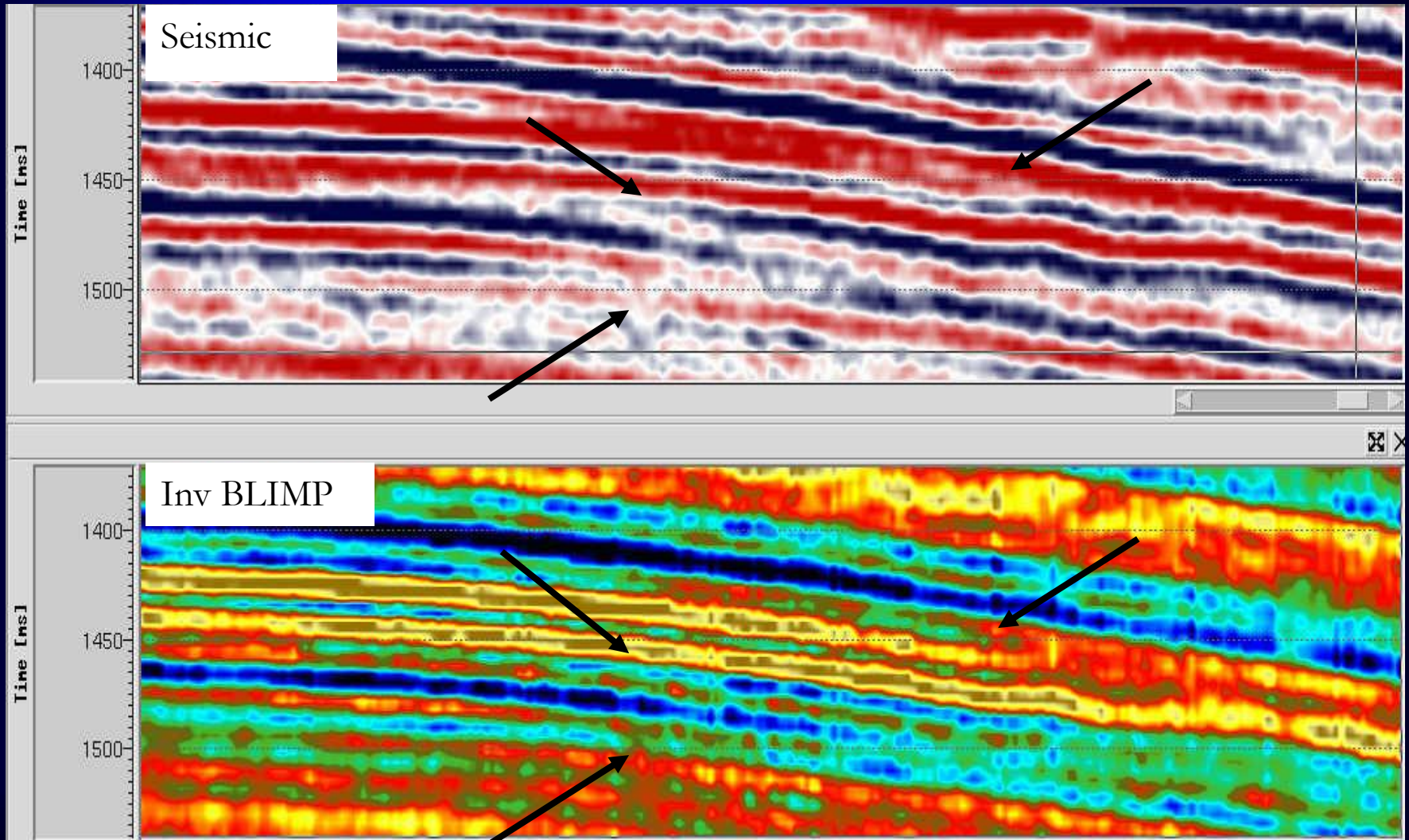
Summary on Seismic Inversion

- Impedance inversion allows fluid determination in the reservoir rocks: Gas or water (oil with gas in solution)
- Well log conditioning is key for constraining inversion
- Seismic inversion is not a unique process. Several AI models can generate similar synthetic traces when convolved with the wavelet. The number of possible solutions is significantly reduced by putting constraints on the modeling.
- Stratigraphic interpretation is improved

Summary on Seismic Inversion

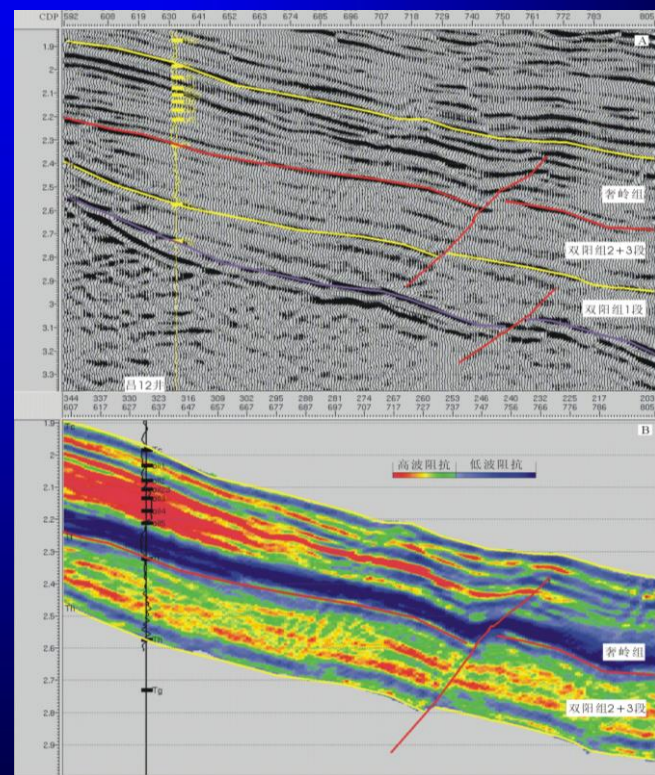
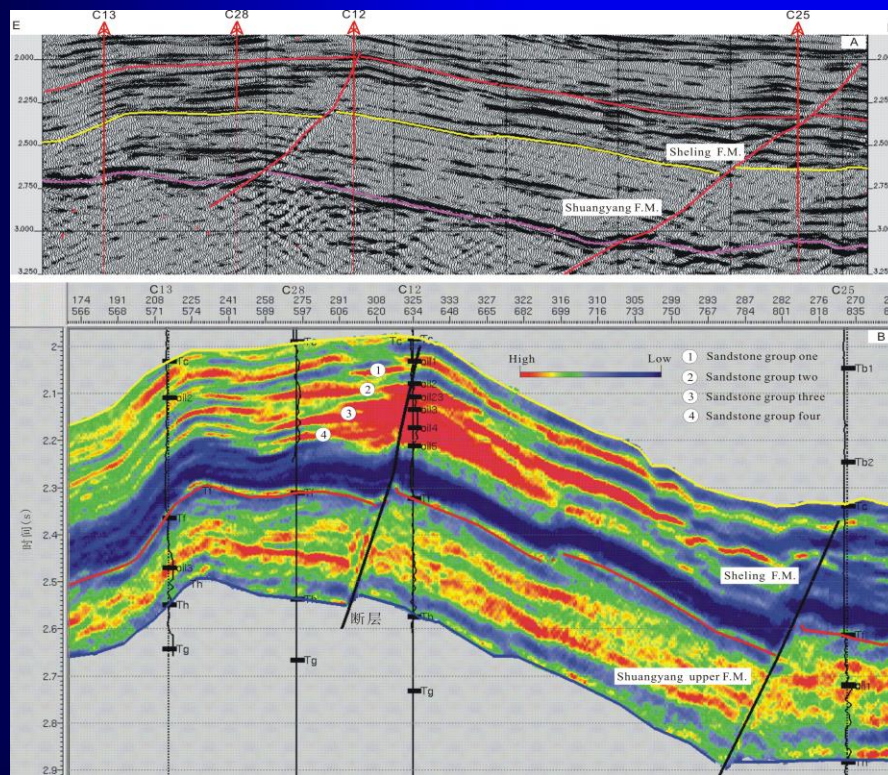
- Seismic impedance volume allows the integration of seismic amplitudes for reservoir characterization.
- The analysis of 3D seismic data in terms of acoustic impedance provides rock parameter estimation: porosity, permeability, shale volume, net sand, etc.
- 3D acoustic impedance “soft data” for geostatistical model of rock properties

Improving Resolution with Inversion Carbonate Example



Post-Stack Inversion

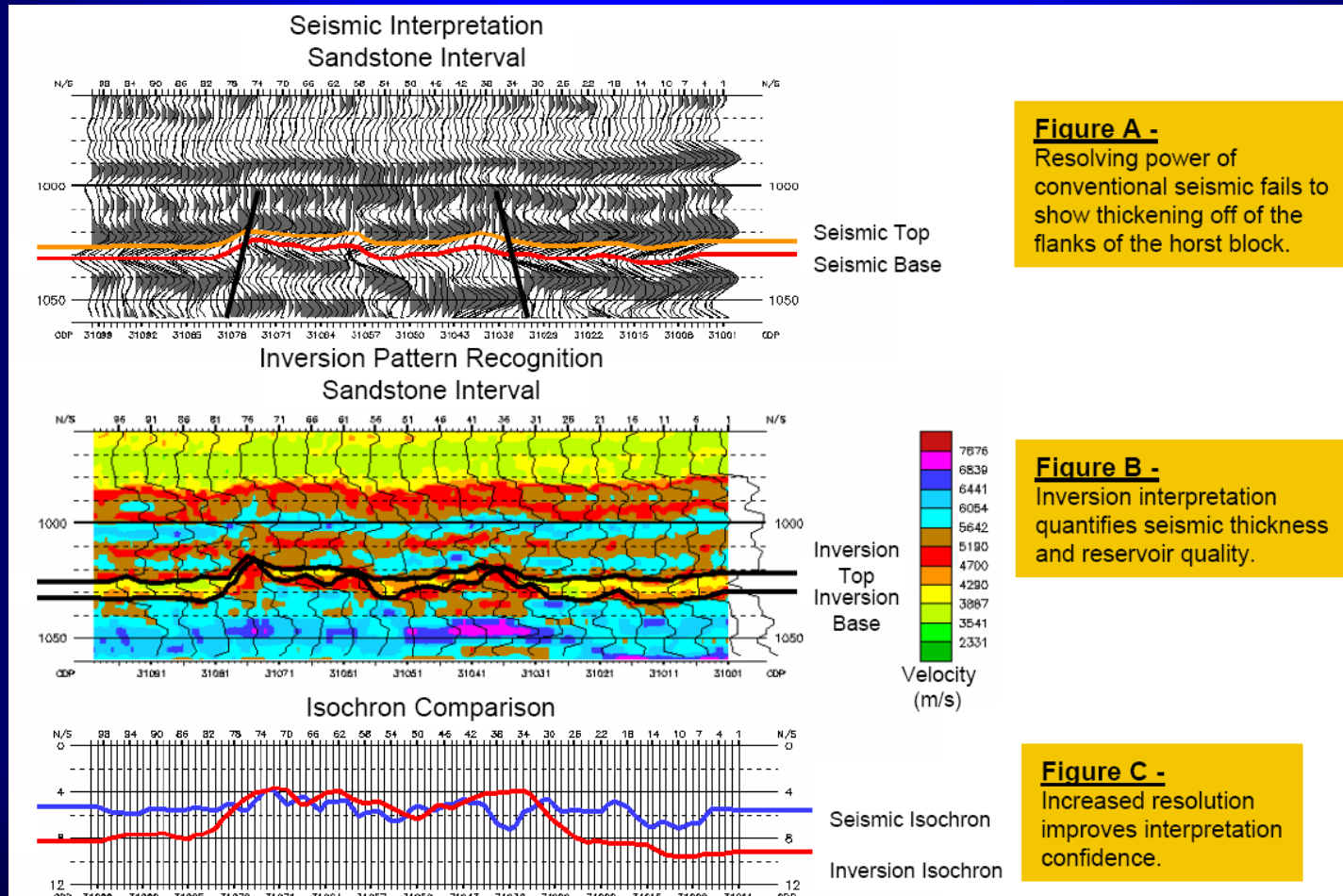
The fan delta respectively by the seismic section and the impedance section, A is seismic section, B is impedance section



Seismic inversion methodology

- Use either convolution or wave equation algorithm to relate impedance to reflectivity
- **Estimate the source wavelet from well data and seismic!**
- Constrain solution near well to honor logs
- Use conventional interpretation of the phase (time structure maps) to constrain lateral impedance correlation via a smooth or blocky background model
- Provide low frequency component of impedance from wells and kinematic velocity analysis
- Use either local or global constrained optimization methods to fit modeled seismic data to measured seismic data
- Obtain rock properties from AVO data
- QC results by comparison with log data
- Predict lithology and fluid prediction through cross plotting
- Determine hydrocarbon volumes for production

Seismic Inversion Motivation



Seismic Inversion Motivation

1. Acoustic Impedance is tightly correlated with porosity and other lithologic features of interest
2. Band-limited acoustic impedance data have higher resolution than conventional seismic data
3. Careful 3-D acoustic impedance inversion requires detailed wavelet estimation and background model generation, typically taking months of time, and requiring a highly trained expert

Seismic Inversion limitation

1. Only appropriate when the wavelet from a single well ties other wells

Summery

- Modern acoustic impedance inversion algorithms integrate seismic data, well control, estimations of the source wavelet, and interpreter constraints on structure and lithology in a mathematically rigorous manner
- Acoustic impedance 'deconvolves' the seismic data to remove the source wavelet shape
- For the above reasons, acoustic impedance has higher resolution than conventional seismic data
- Of all the attributes, acoustic impedance is one of the most closely tied to rock porosity
- Elastic impedance and extensions of classical AVO analysis, promise to provide high resolution estimates of lithology and fluid product

Benefits of 3D Inversion

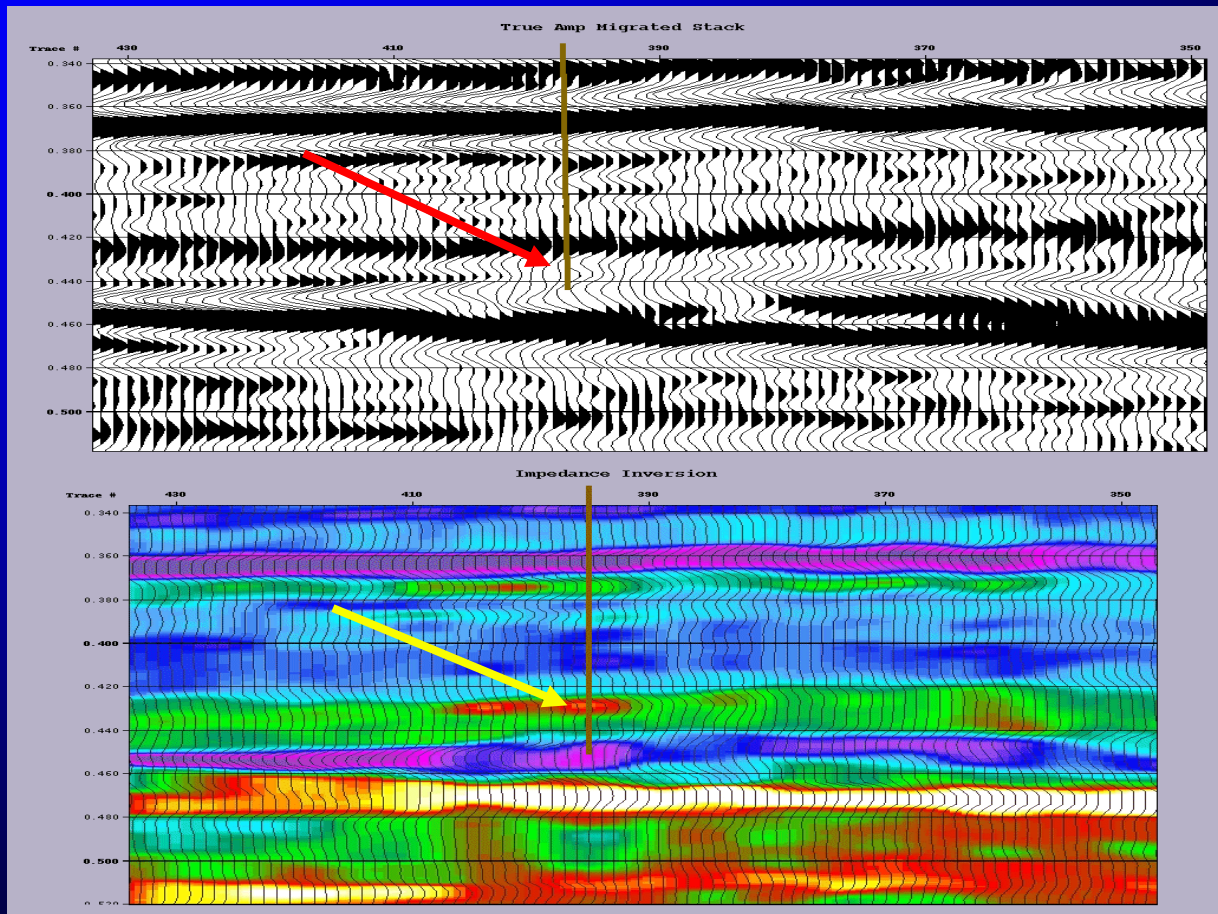
- **Lithology and Fluid Discrimination**
- **Used for Reservoir Property Prediction**
- **Best Tool for Reservoir Characterization**
- **Best Method for Optimized Field Development**
- **Increased Reflectivity in Shear Volume**
- **Calibration to Well Data and Rock Properties**
- **Increased Signal Bandwidth**
- **Easier to Interpret**

Deliverables

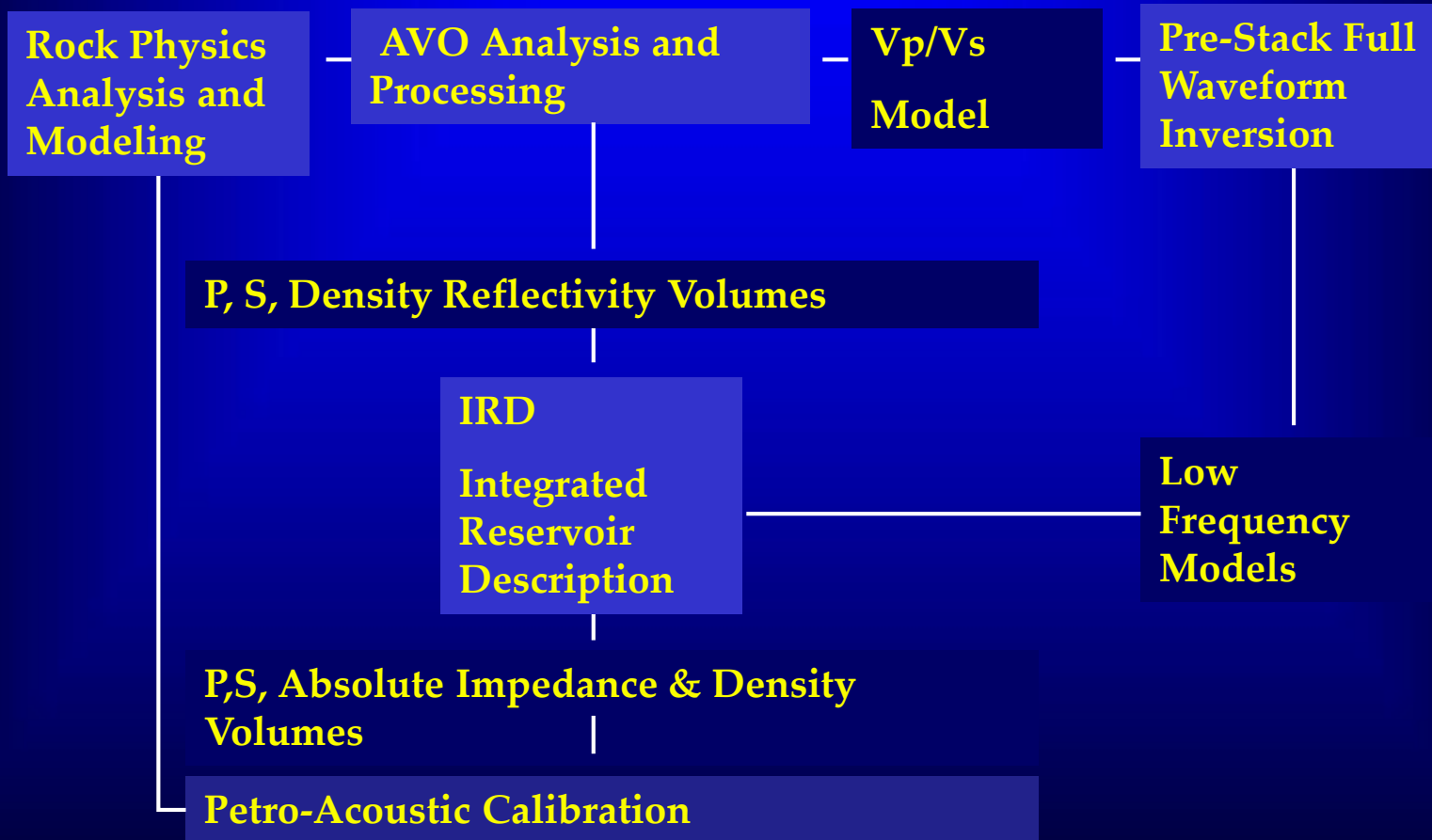
- **Acoustic Impedance Volume** (Product of Velocity and Density)
 - Porosity, Geometry and Lithology
- **Shear Impedance Volume**
 - Lithology, Fluid
- **Density Volume**
 - Fluid type and 'fizz water' discriminator
- **Vp/Vs Volume** or
- **Poisson's Ratio Volume**
 - Lithology, Fluid type, Net/Gross ratio's
- **Porosity Volume**

- **N/G and Sw Estimations**

Easier to Interpret



Inversion Workflow



Quality Control of Inversion Process

- Well logs should be examined for suitable relationships between measured impedance logs (calculated by dividing the density by the the sonic log) and properties such as porosity and fluid type
- Well Logs should be converted to time and edited for borehole effects, balanced, and classified based upon quality
- Synthetics should be generated for all wells. Logs that do not tie should be investigated for problems in log, wavelet, or seismic
- It is generally preferable to run a loosely constrained trace based inversion first (possibly augmented by non seismic data such as trend data from velocities or wells) to use for interpretation of a more tightly constrained model for later use in a model based inversion

Quality Control of Inversion Process

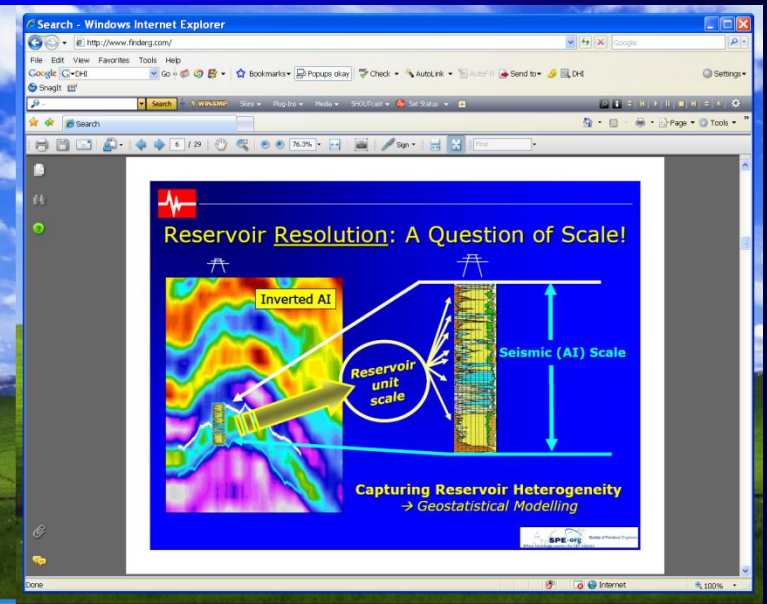
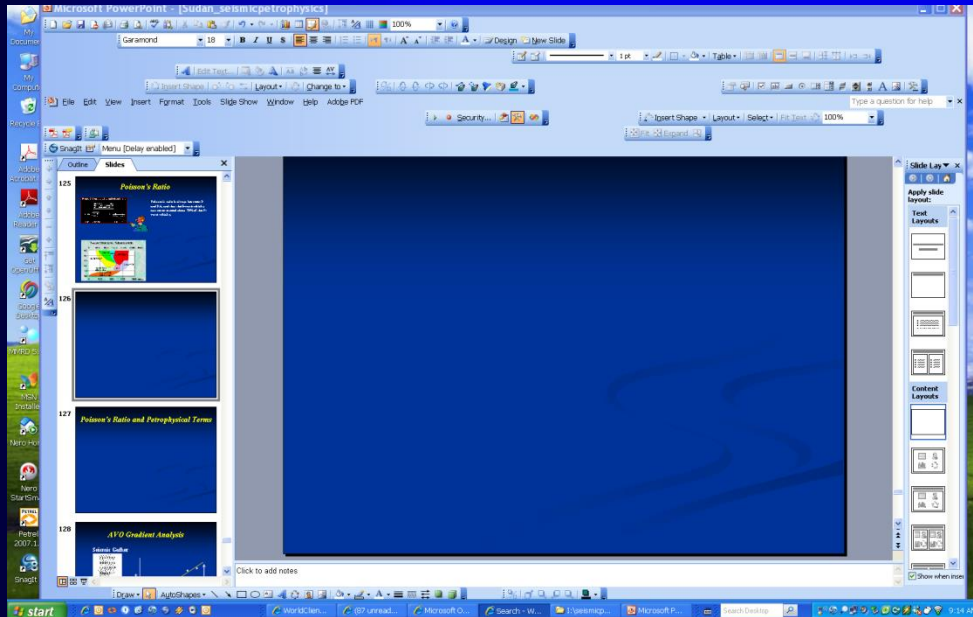
- The main test of inversion accuracy is how well it ties to the input data
- Volumes that rely heavily on log derived models should match the logs at the well locations
- More model based volumes should match the seismic and the synthetic created after inversion
- To make a valid comparison between log data and inverted impedance the log data should be filtered to the range of the seismic frequencies
- In all cases a universal check is to compare the model to well data that was not included in the processing - a “blind” accuracy test

Quality Control of Inversion Process

If results of the inversion do not tie and you have correctly processed logs then check the wavelet

- an inversion should be done over a time target with a wavelet extracted from that interval
- if a wavelet from deeper is used it may have too low of frequency and can result in “ringing”
- if a higher frequency wavelet from a shallower interval is used deeper than results will appear smeared
- wavelets with an incorrect phase or amplitude spectrum can result in erroneous time shifts that contain extra side lobes and create false geological features

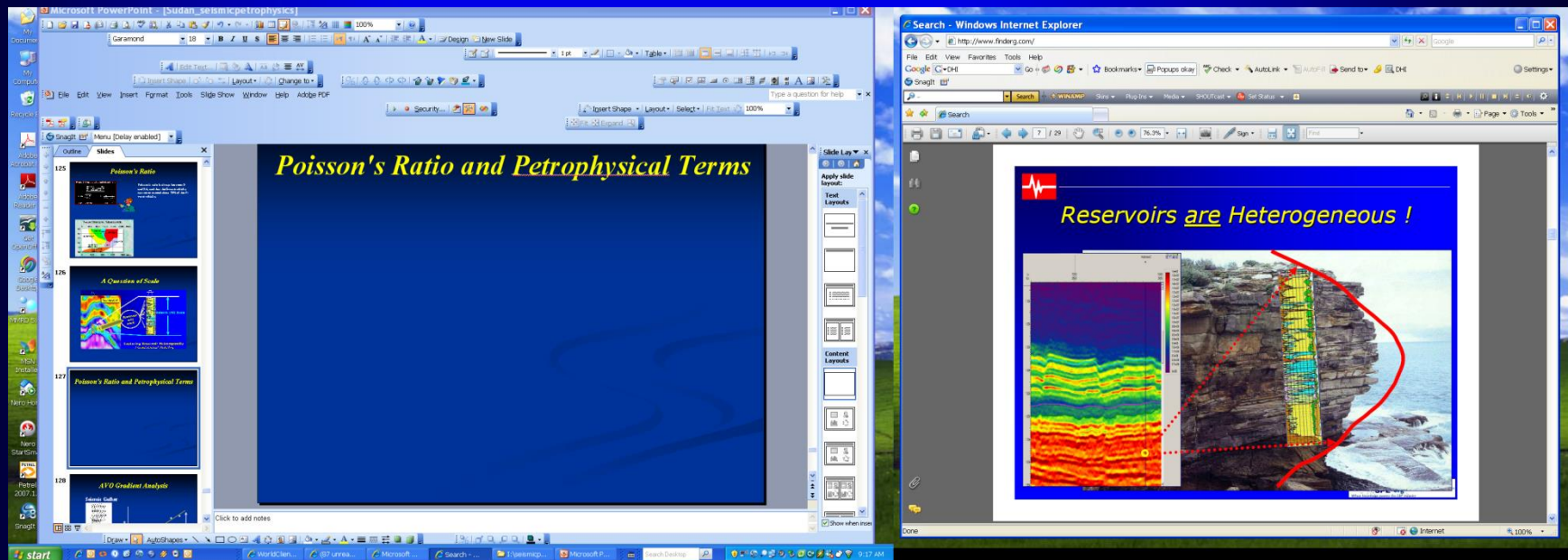
Question of Heterogeneous Reservoirs



ALI BAKR

Dr ALI BAKR, Prof R. B. Latimer

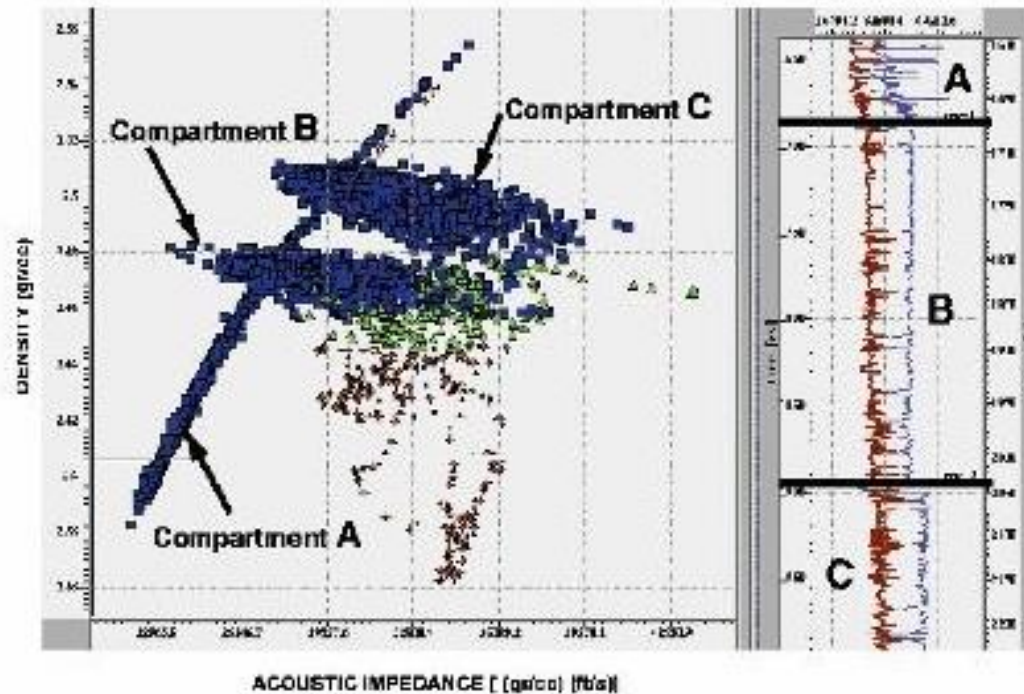
Quality Control of Inversion Process



ALI BAKR

Dr ALI BAKR, Professor R. B. Latimer

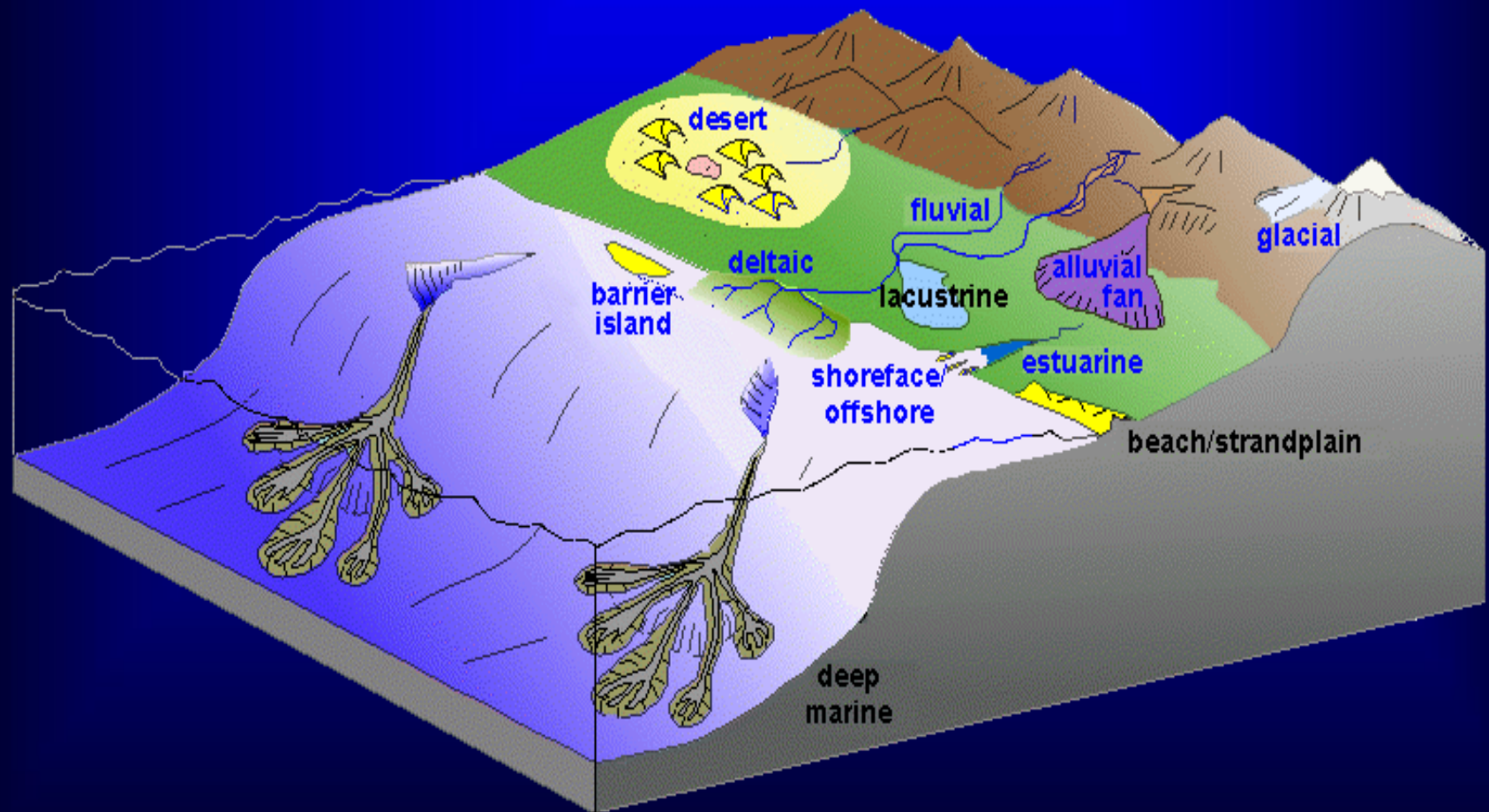
Establishing a Relationship Between AI and Lithology



Crossplot of acoustic impedance versus density showing three distinct compaction trends. Blue, green, and red dots identify shales/tuffs, tight sands, and porous sands, respectively.

5-SEISMIC STRATIGRAPHY

SEISMIC STRATIGRAPHY

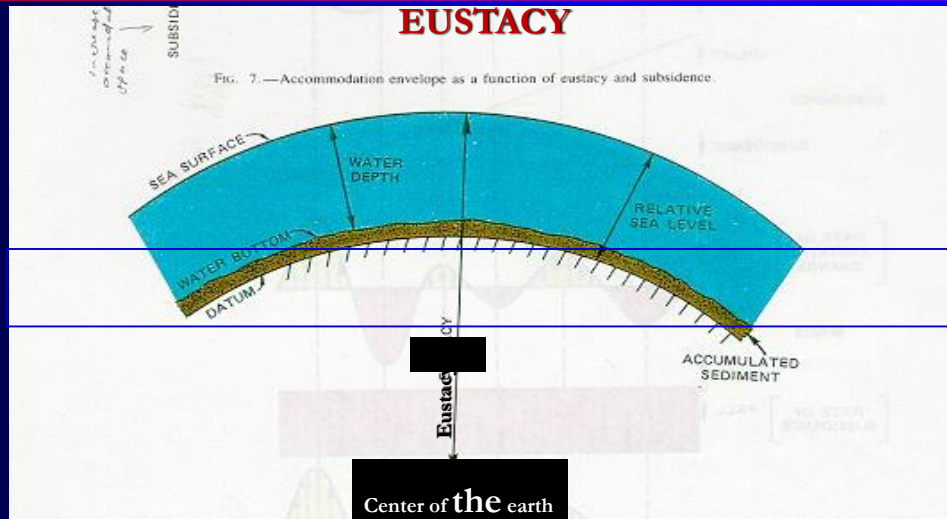


Fundamental Sequence Stratigraphic Concepts

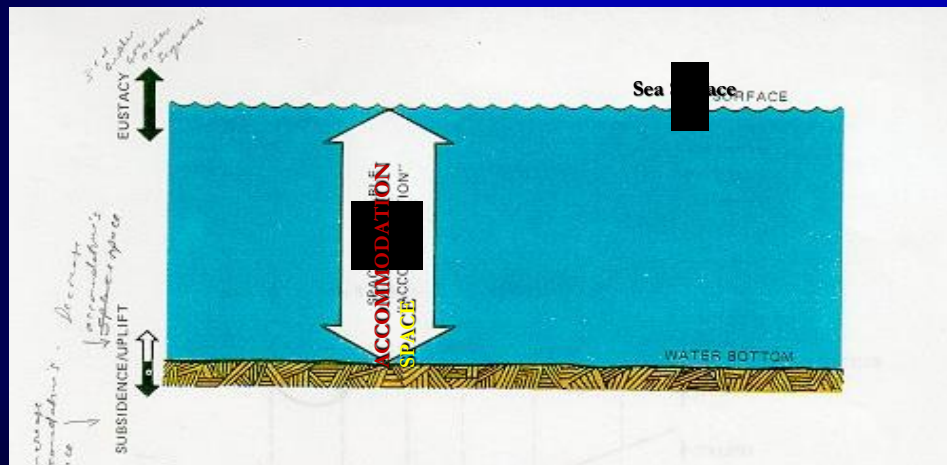
Orders of Stratigraphic Cyclicity

ORDER	DURATION (M.Y.)		STRATIGRAPHIC NOMENCLATURE		SCALE	Seismic
	RANGE	MODE				
1st	350 - 500	450	Megasequence Set		Major Systems and Basins <i>> 1000's of meters</i>	
	50 - 100 +	80	Megasequence			
2nd	20 - 50 +	30	Supersequence Set		Systems and Series <i>100's 10 1000's of meters</i>	
	5 - 20 +	10	Supersequence			
3rd	0.5 - 5	1	GREENHOUSE Sequence	ICEHOUSE Composite Sequence	Fields <i>10's to 100's of meters</i>	
4th	0.05 - 0.5	0.1; 0.45	Parasequence Set Parasequence	High Frequency Sequence	Fields and Reservoirs <i>1 - 10's of meters</i>	
5th	0.01 - 0.05	0.02; 0.04	Parasequence Bed Sets	Parasequence Set Parasequence	Reservoirs <i>< 1m to a few meters</i>	
> 6th	< 0.01		Beds Laminae	Bed Sets Beds Laminae	<i>< 1m</i>	Outcrops and Cores

Sea Level Fluctuations



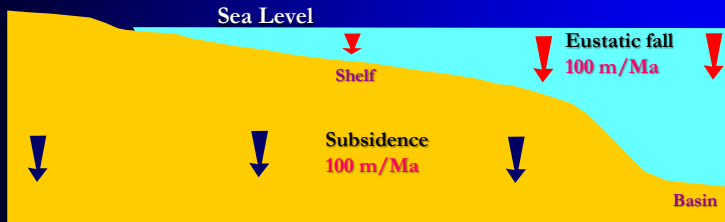
Eustacy = Global sea level measured from center of earth



Relative Sea Level:-
Position of the sea surface relative to a datum (I.e basement/sea bed) and hence incorporates local subsidence/uplift

Sea Level Fluctuations

Rate of Eustatic fall = Rate of Subsidence



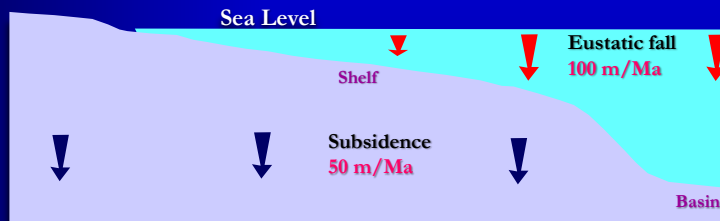
Basin A

Sea Level Drop = 100 m

Subsidence = 100 m

No change in relative sea level

Rate of Eustatic fall > Rate of Subsidence



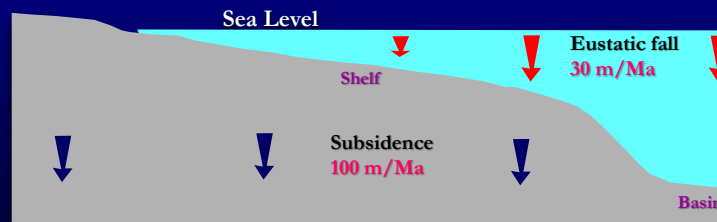
Basin B

Sea Level Drop = 100 m

Subsidence = 50 m

Relative sea level dropped by 50 m

Rate of Eustatic fall < Rate of Subsidence



Basin C

Sea Level Drop = 30 m

Subsidence = 100 m

Relative sea level
raised by 70 m

Seismic Stratigraphy

- Why doing seismic stratigraphy?
- Scale of seismic stratigraphy study
- Time concept in Seismic Straigraphy
- Assumptions
- Categories

Seismic Stratigraphy

Why doing Seismic stratigraphy?

- Geological age correlations
- Thickness estimates
- Environment of deposition
- Paleobathymetry
- Burial history
- Relief
- Topography on unconformities
- Lithology
- Porosity/permeability
- Fluid content
- Insight into source and seal

Seismic Stratigraphy

Scale of Study

There are three scales for seismic stratigraphy studies:

- **Regional Scale Seismic Strat-Interpretation** – Large-scale stratigraphic interpretation of data “seismic stratigraphy”.
- **Prospect Scale Seismic Strat-interpretation.** Localized interpretation to define a prospect. May include use of reflection configurations, wave shape, amplitude, etc.
- **Reservoir scale Seismic Strat-interpretation.** Quantitatively characterize reservoir (net sand, ϕ -H, etc.) to permit reserve determination, reservoir simulation ,etc...

Seismic Stratigraphy

- Why doing seismic stratigraphy?
- Scale of seismic stratigraphy study
- Time concept in Seismic Straigraphy
- Assumptions
- Categories

Concept of complete continuous time

- The earth doesn't shut down with each stratigraphic cycle;
- There are no gaps in the stratigraphic record and time is not missing;
- Unconformities and hiatal surfaces at one geographic location are time equivalent to strata at another geographic location.
- The unconformities which bound a stratigraphic sequence at one location disappear and are replaced by continuous rock successions at another location.

Seismic Stratigraphy

- Why doing seismic stratigraphy?
- Scale of seismic stratigraphy study
- Time concept in Seismic Straigraphy
- **Assumptions**
- Categories

Seismic Stratigraphy

Assumptions for Reflection Character Analysis

- Reflections are boundaries of impedance contrast.
- Reflections have areas in excess of the first Fresnel zone or .
- Reflections are from bedding surfaces.
- Reflections parallel time/age lines.

2-Seismic Stratigraphy

- Definitions
- Why doing seismic stratigraphy?
- Time concept in Seismic Straigraphy
- Scale of seismic stratigraphy study
- Assumptions
- Categories

Seismic Stratigraphy

Categories

Seismic stratigraphy is divided into two main categories:

- **Reflection- character analysis**
- **Seismic facies analysis**

2-Seismic Stratigraphy

Categories- Reflection Character Analysis

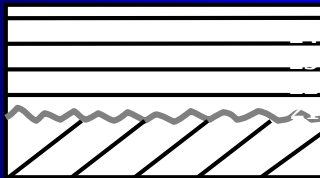
Reflection character analysis

Analyse the lateral variation of an individual reflection unit or units in order to localise where stratigraphic changes are found and identify their nature.

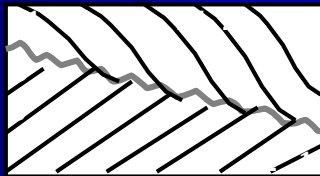
Seismic Stratigraphy

Categories- Reflection Character Analysis

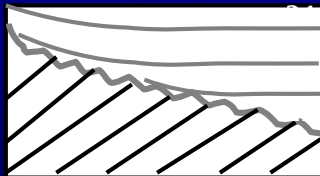
Reflector terminations defining the upper and lower boundary of a sequences



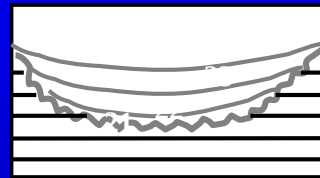
Concordant above
Erosional: angular, structural



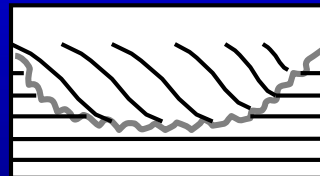
Downlap above
Erosional: angular, structural



Onlap above
Erosional: angular, structural



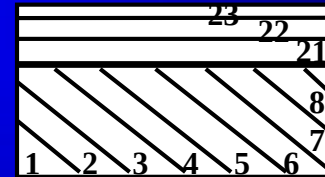
Onlap above
Erosional: angular, nonstructural



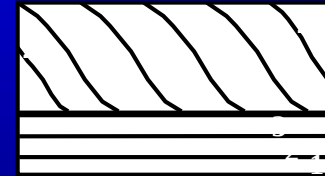
Downlap above
Erosional: angular, nonstructural



Onlap above
Tilting or original depositional attitude



Concordant above
Toplap below



Downlap above
Concordant below

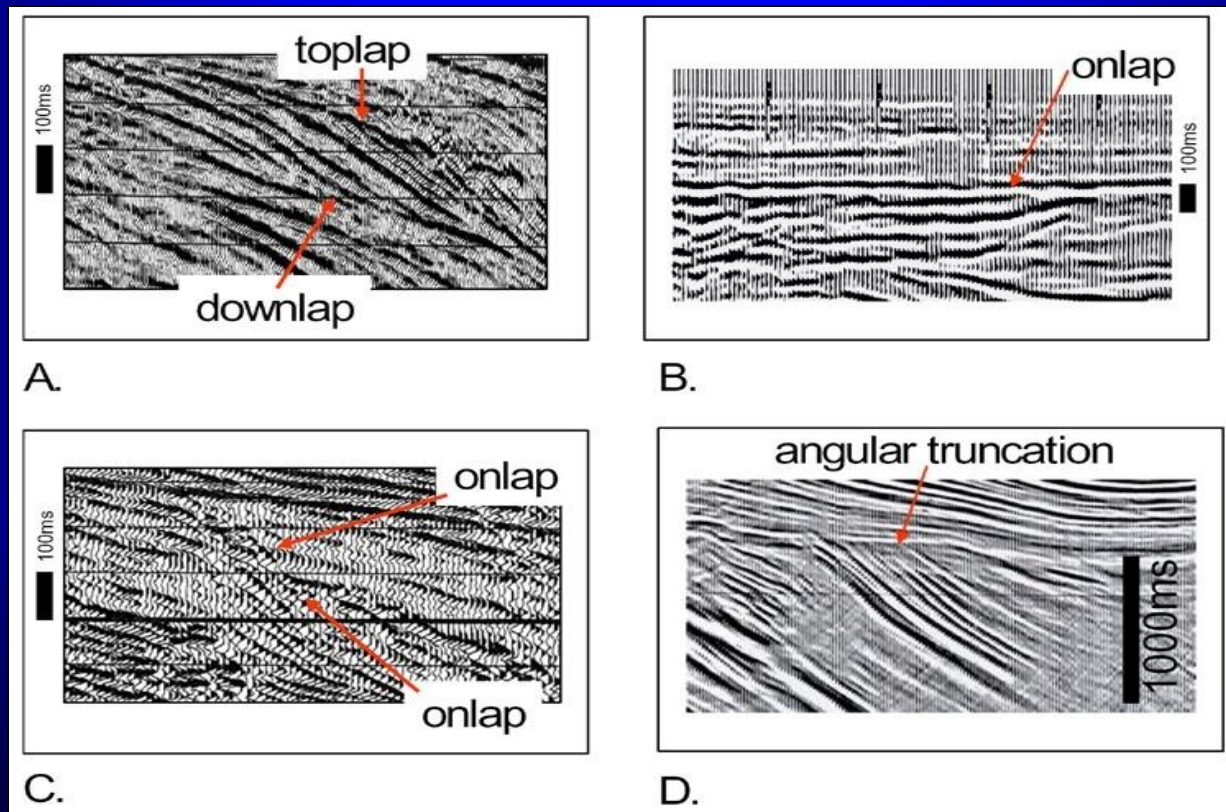


Concordant above
Concordant below

2-Seismic Stratigraphy

Categories- Reflection Character Analysis

Reflector terminations defining the upper and lower boundary of seismic sequences



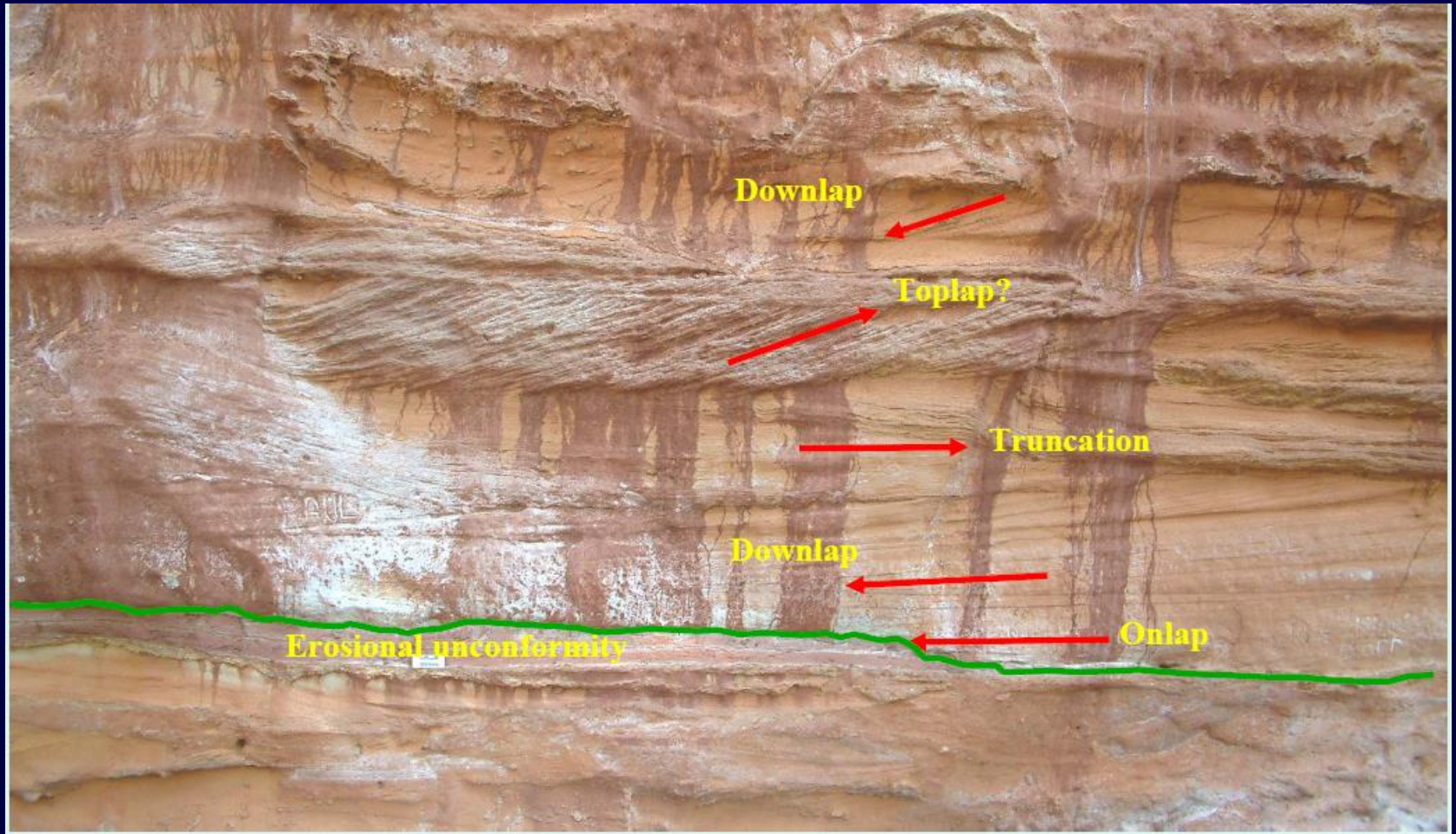
2-Seismic Stratigraphy

Categories- Reflection Character Analysis



2-Seismic Stratigraphy

Categories- Reflection Character Analysis

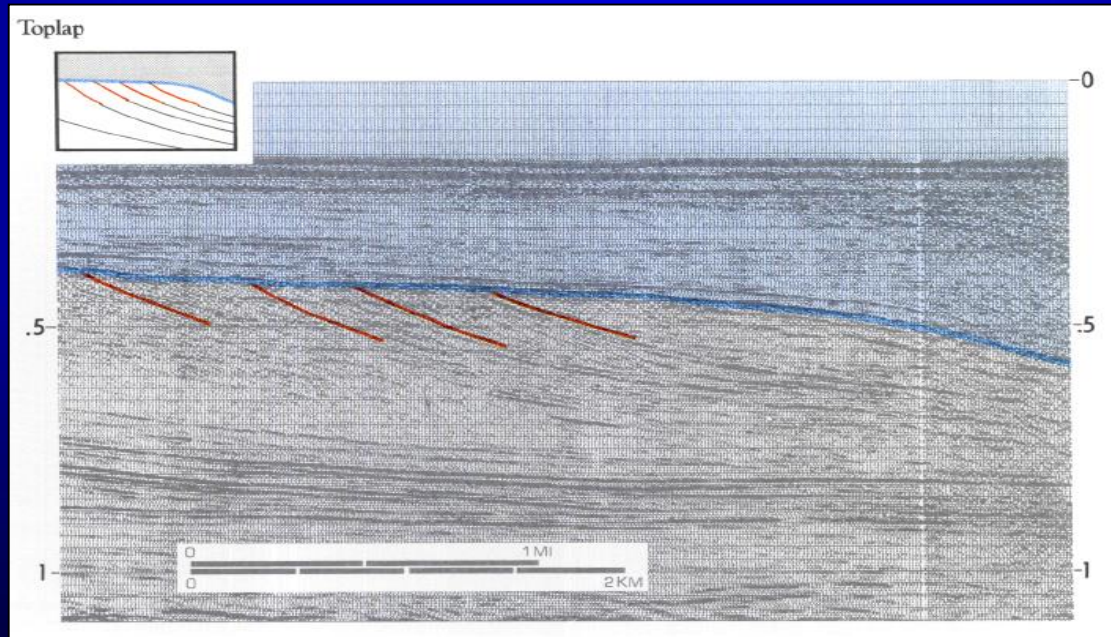


Seismic Stratigraphy

Categories- Reflection Character Analysis

Toplap (Upper Boundaries)

It is a termination of strata, or seismic marker, against an overlying surface mainly resulting of non-deposition (sedimentary bypassing) with perhaps only minor erosion. Each unit of strata laps out in a landward direction at the top of the unit, and each successive termination lies progressively seaward.



Seismic Stratigraphy

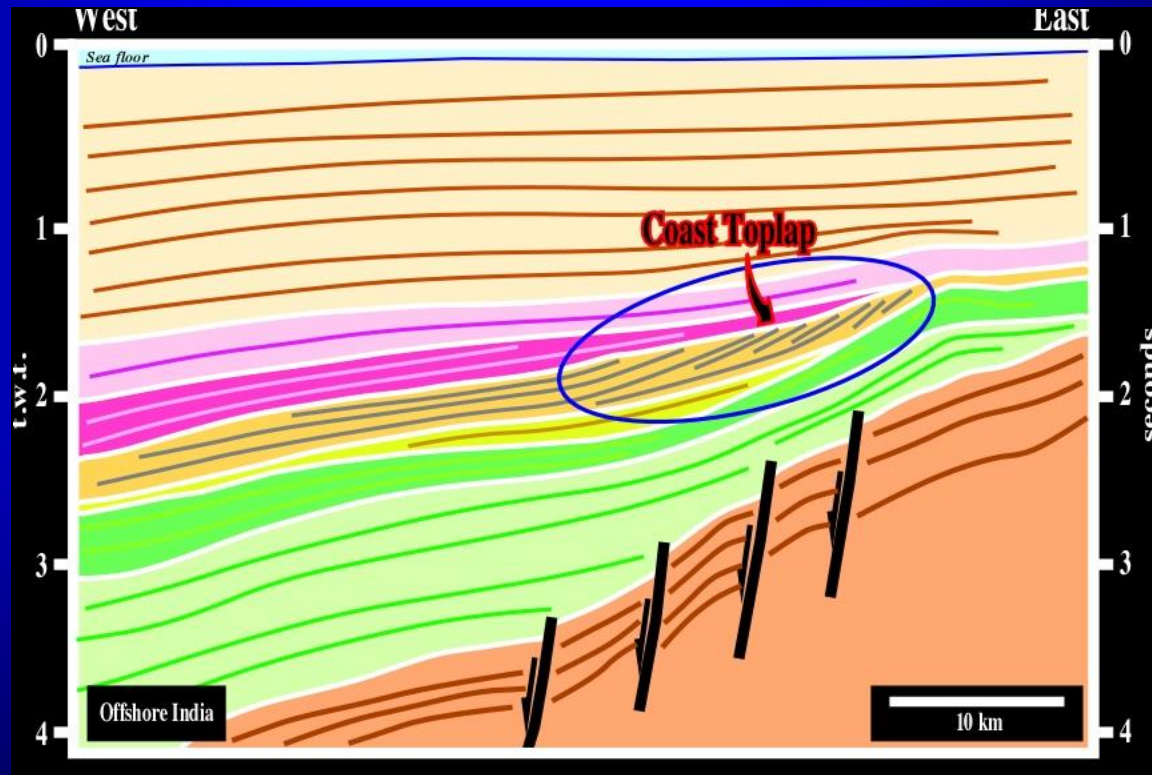
Categories- Reflection Character Analysis

Toplap

- 1- Coastal toplap
- 2- Marine toplap
- 3- Non-marine toplap

2-Seismic Stratigraphy Reflection Character Analysis

Toplap

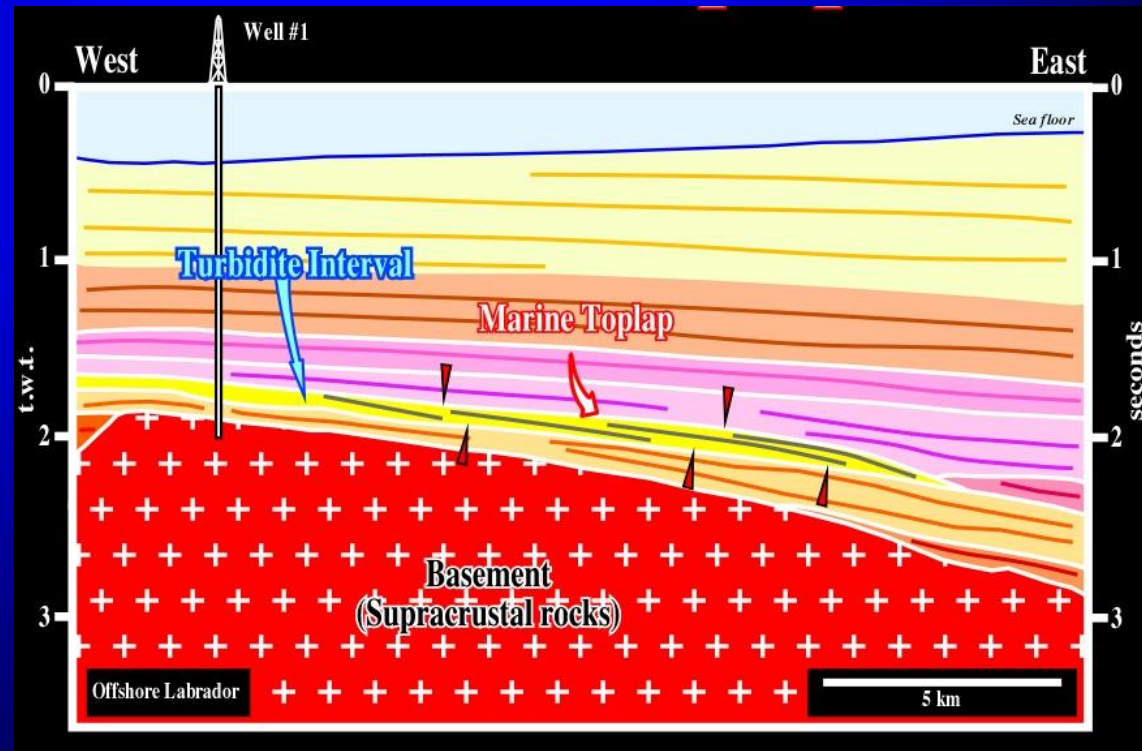


1- Coastal toplap

Seismic Stratigraphy

Reflection Character Analysis

Toplap

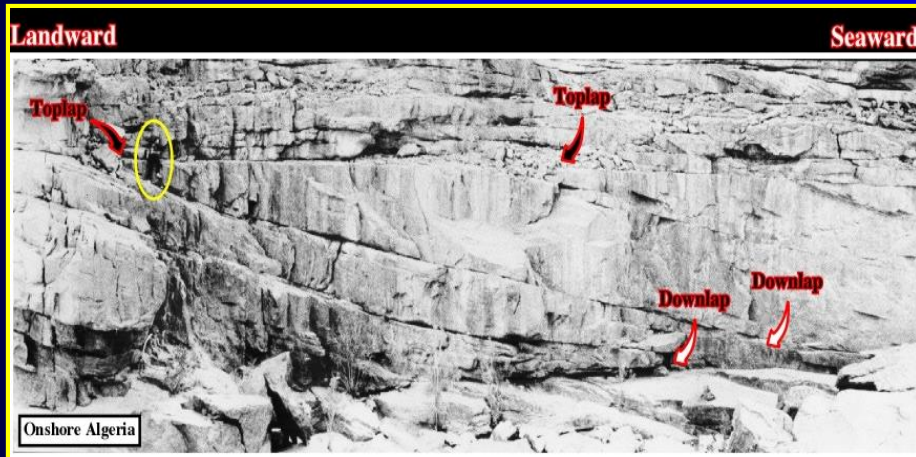


2- Marine tolap

Seismic Stratigraphy

Reflection Character Analysis

Toplap

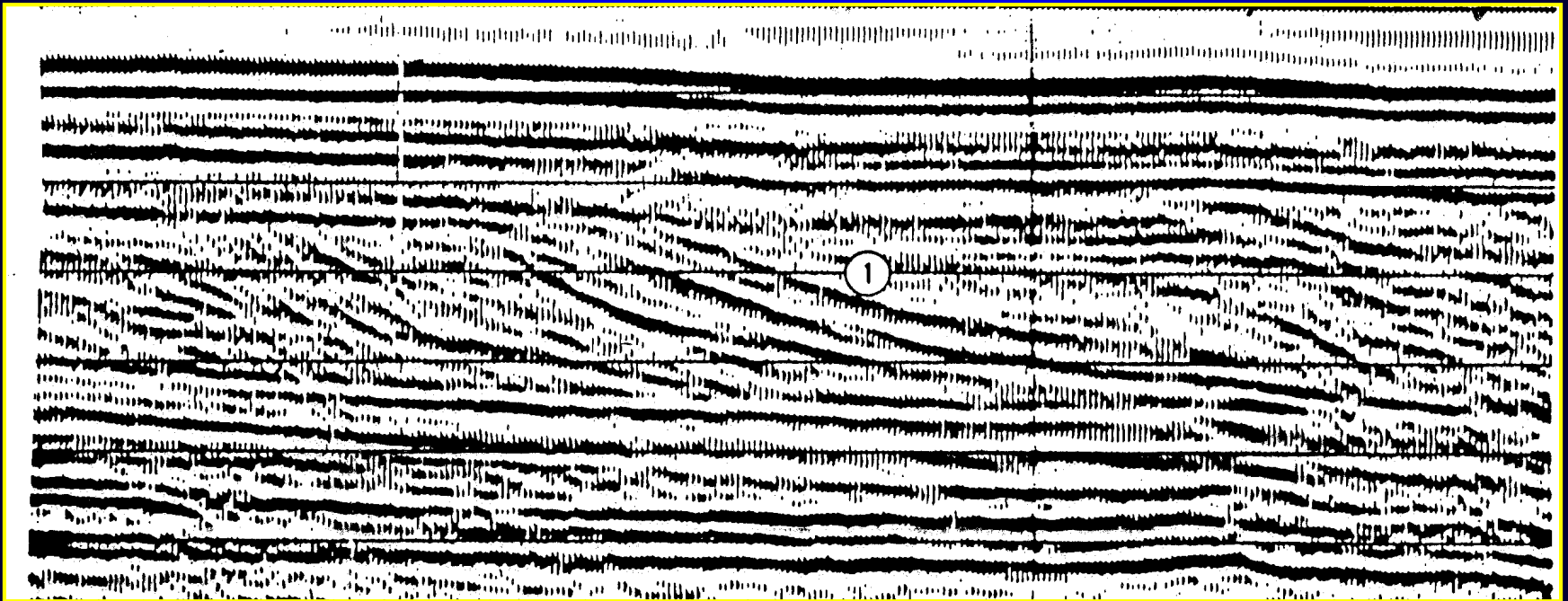


3- Non-marine tolap

Seismic Stratigraphy

Categories- Reflection Character Analysis

Mark Toplap (Upper Boundaries)

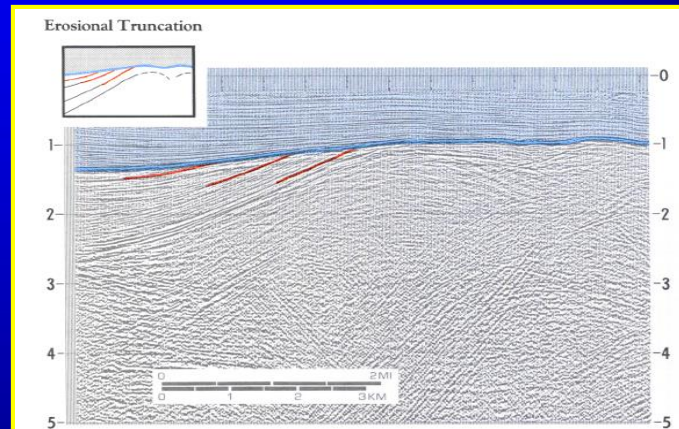
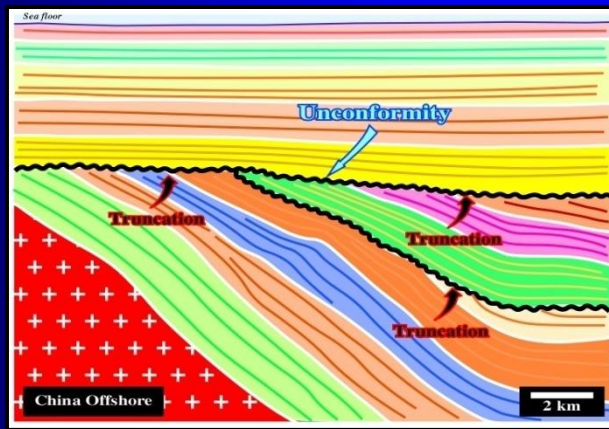


2-Seismic Stratigraphy

Categories- Reflection Character Analysis

Erosional truncation (Upper Boundaries)

Where inclined strata terminate against an erosional surface.

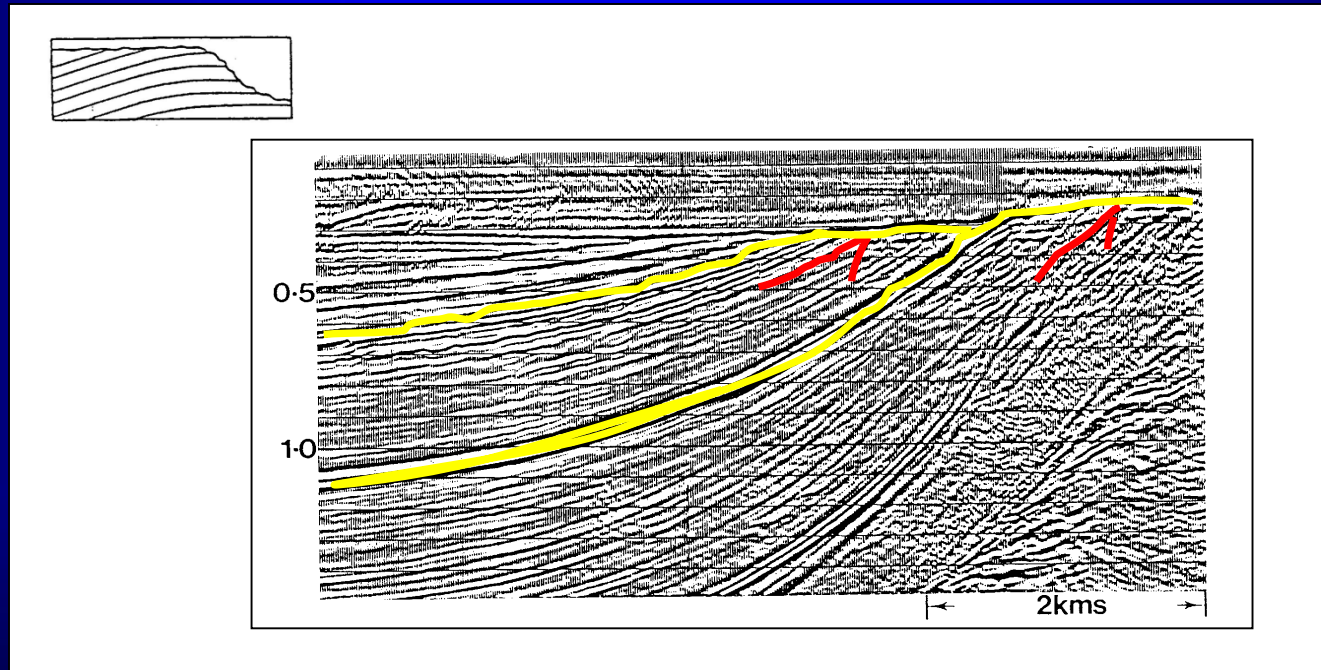


An unconformity is an erosional surface that separates younger strata from older rocks and represents a significant hiatus (at least a correlatable part of a geochronologic unit is not represented by strata). In very particular cases, an unconformity can corresponds to an non-depositional surface. Periods of erosion and non deposition occur at each global fall of sea level producing interregional unconformities. Although in some areas of continuous deposition, the hiatus may be too small to be detected paleontologically or seismically, and the surface is defined as a conformity.

Seismic Stratigraphy

Categories- Reflection Character Analysis

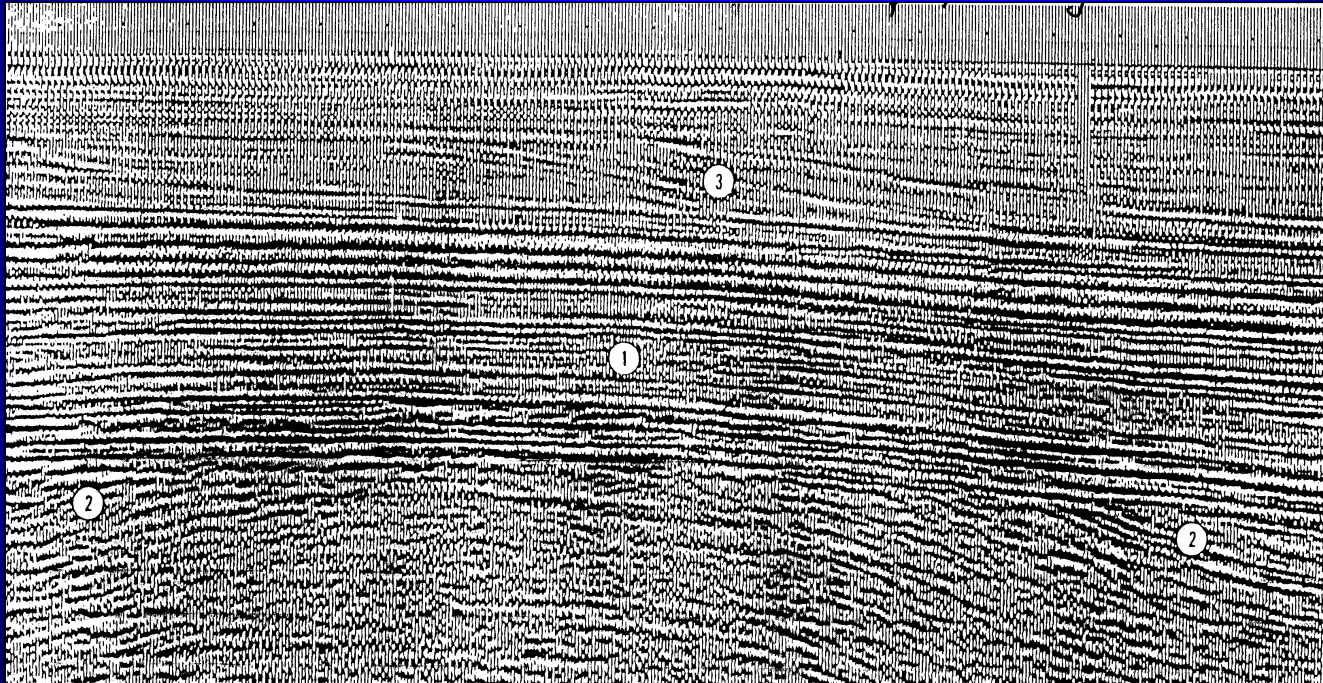
Erosional truncation (Upper Boundaries)



Seismic Stratigraphy

Categories- Reflection Character Analysis

Mark **Erosional truncation** (Upper Boundaries)

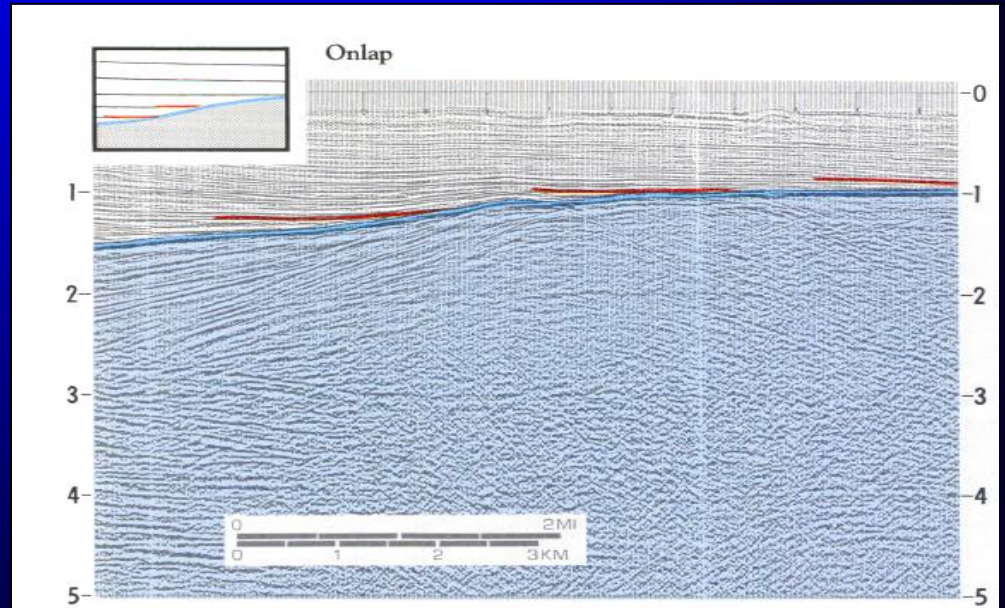
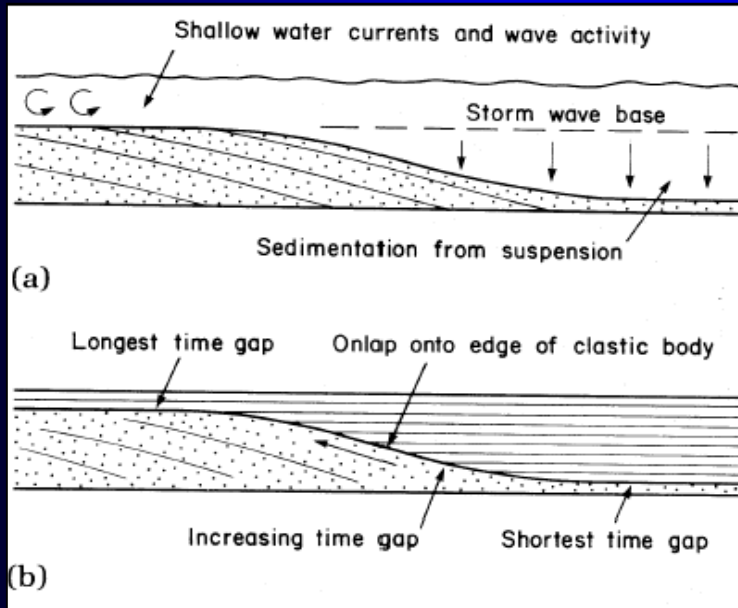


Seismic Stratigraphy

Categories- Reflection Character Analysis

Onlap (Lower Boundaries)

If a period of deposition dominated by bedload transport (sand sized materials) ceases and is followed by a period of deposition from suspended load, then filling the latter ususally produces an onlapping sequence.



Seismic Stratigraphy

Categories- Reflection Character Analysis

Onlap

1-Proximal onlap

2-Distal onlap

3-Coastal onlap

4-Marine onlap

5-Apparent onlap

6-Nonmarine onlap

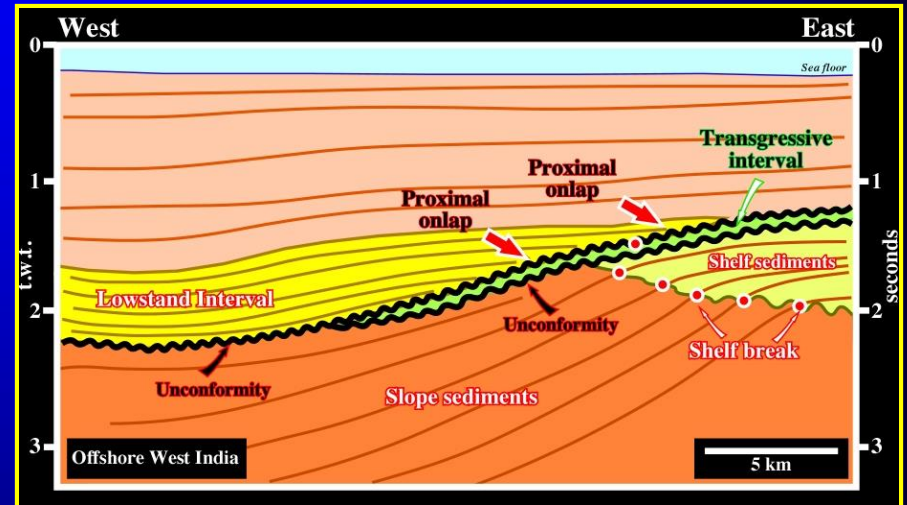
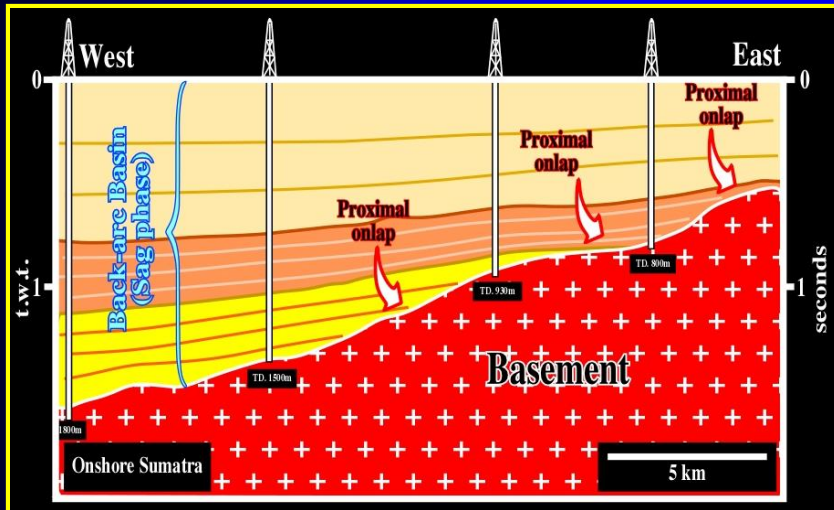
7-True onlap

8-Tilted onlap (Apparent downlap)

Seismic Stratigraphy

Categories- Reflection Character Analysis

Onlap

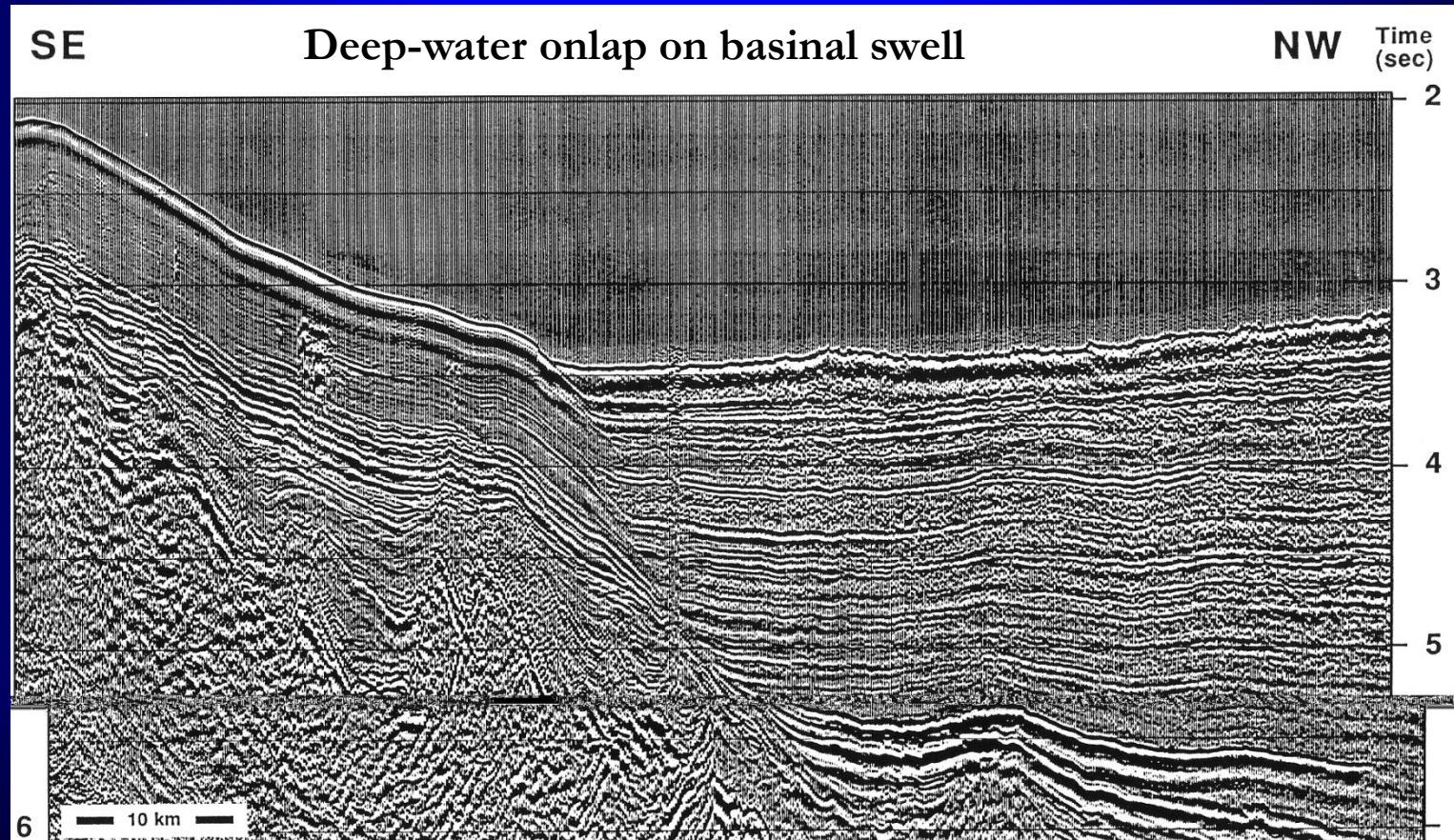


1- Proximal onlap : is onlap in the direction of the source of clastic supply.

Seismic Stratigraphy

Categories- Reflection Character Analysis

Onlap

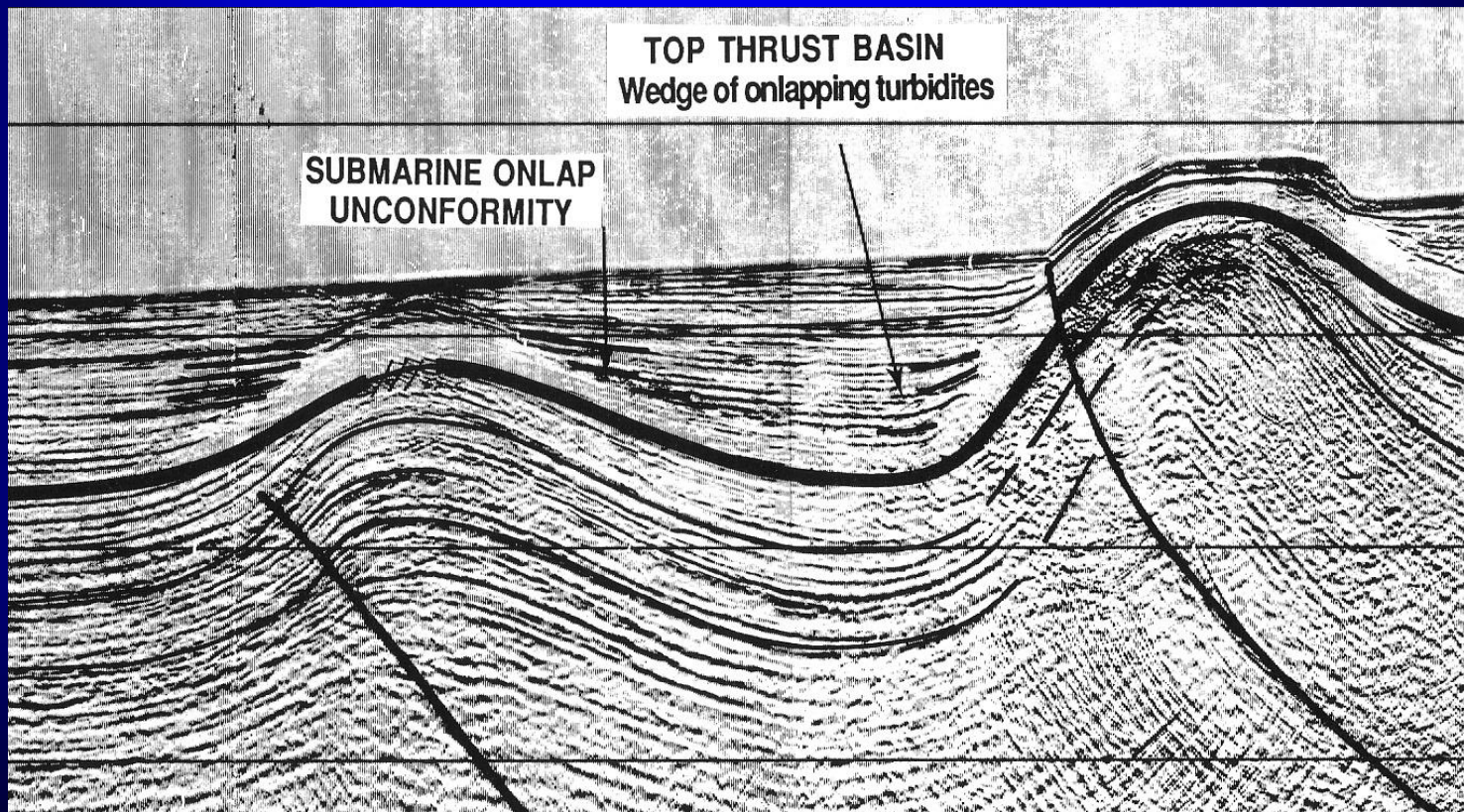


Seismic Stratigraphy

Categories- Reflection Character Analysis

Onlap

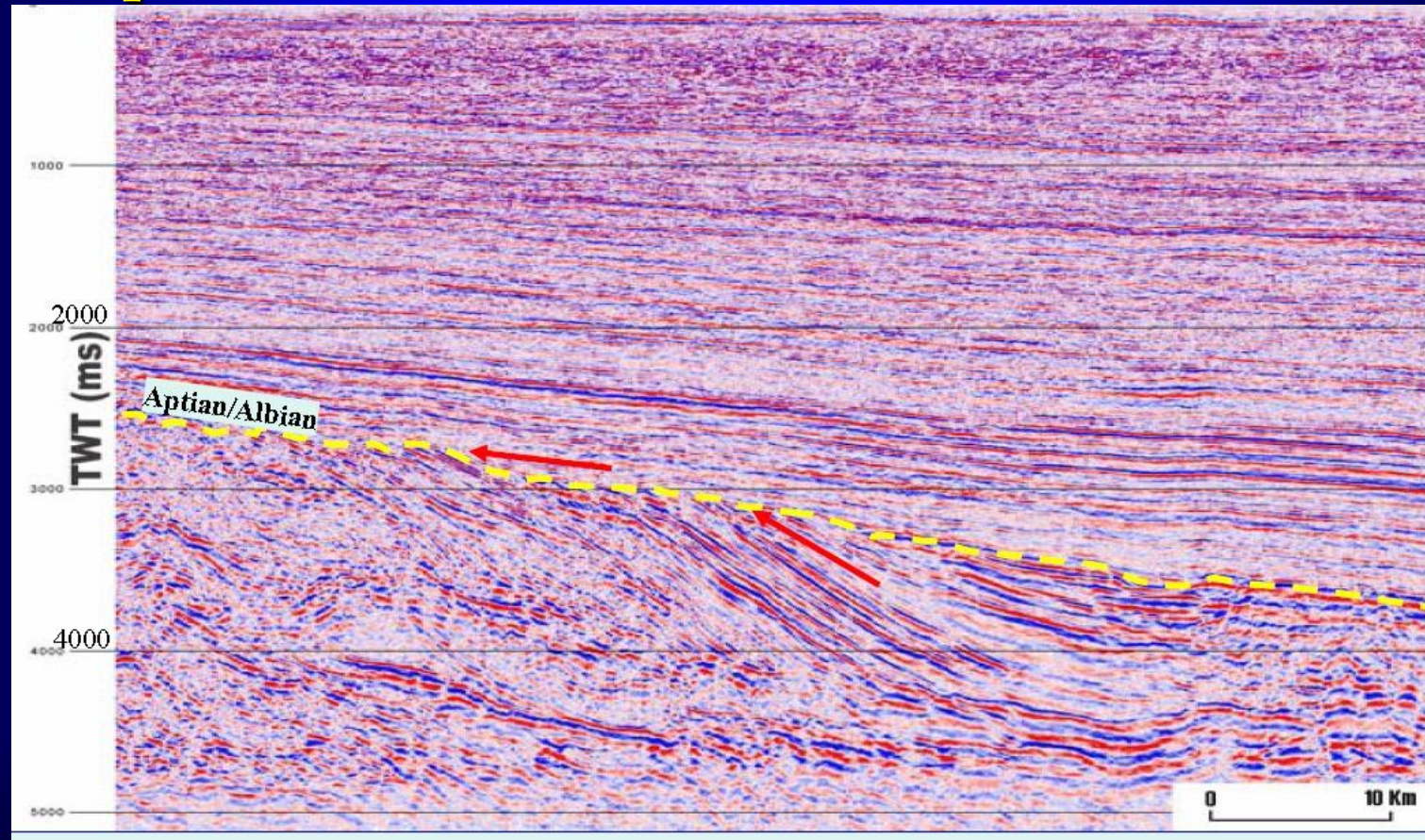
These delta toe-thrusts move during deposition, affecting the depositional process of overlying sequences



Seismic Stratigraphy

Categories- Reflection Character Analysis

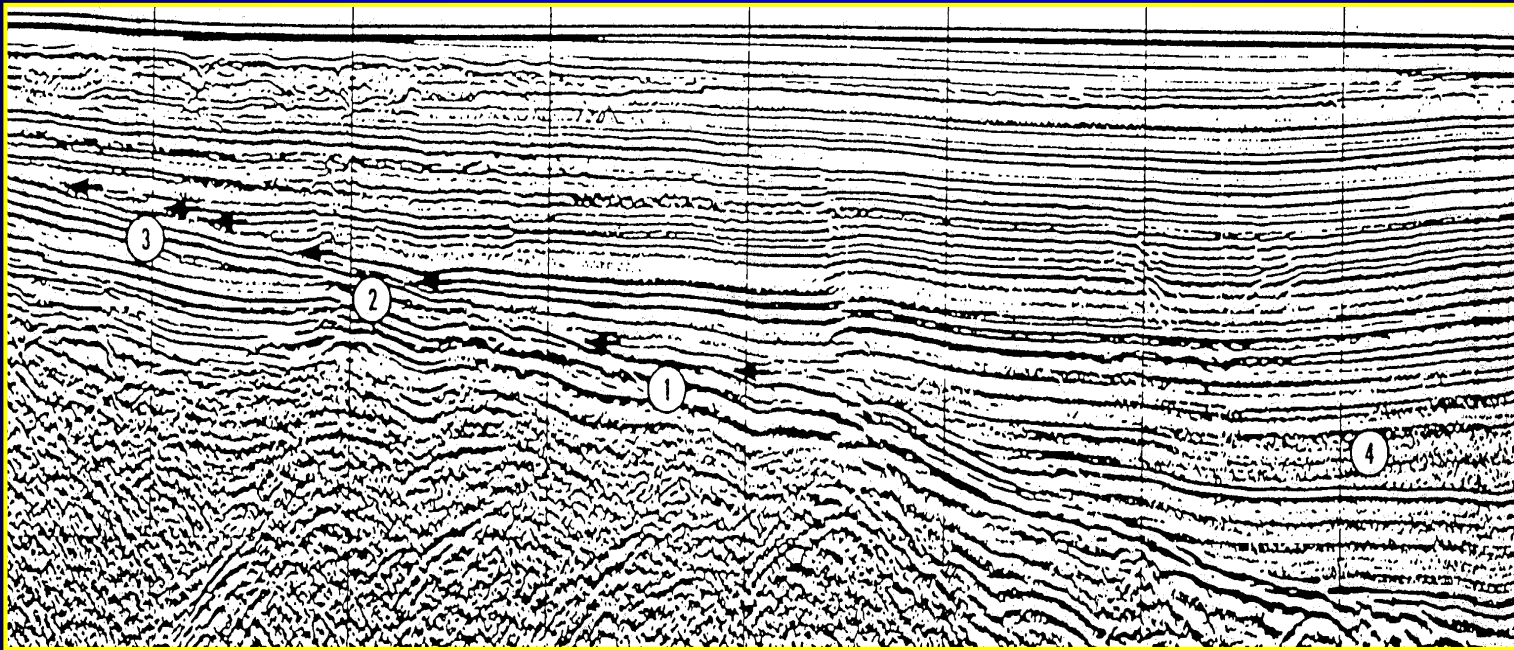
Onlap Onlap & truncation against regional unconformity Aptian



Seismic Stratigraphy

Categories- Reflection Character Analysis

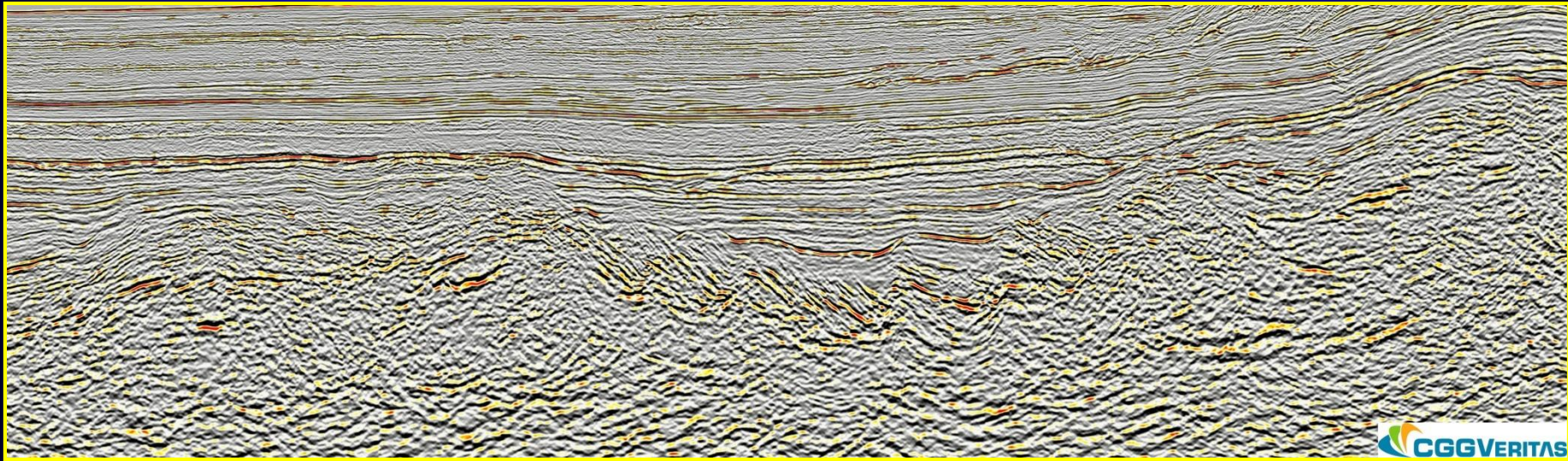
Mark **Onlap** (Lower Boundaries)



Seismic Stratigraphy

Categories- Reflection Character Analysis

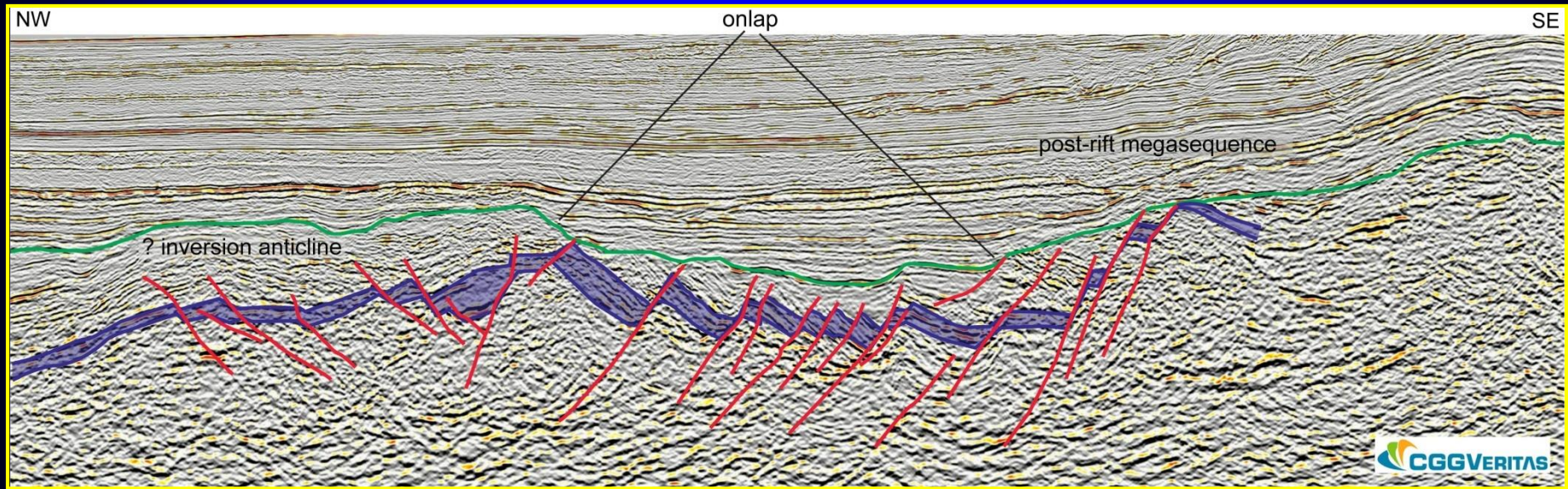
Mark Onlap



Seismic Stratigraphy

Categories- Reflection Character Analysis

Onlap

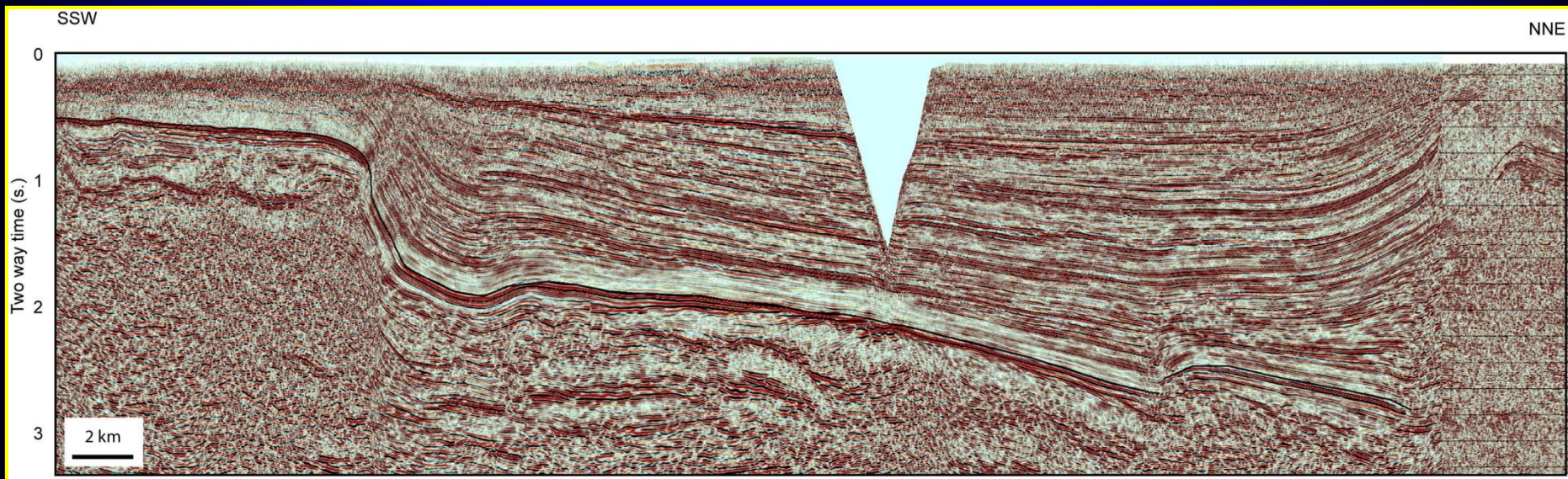


Faulted units beneath the NW continental margin of Australia, blanketed by a post-tectonic sedimentary cover of late Mesozoic and younger age. The faults are shown here as showing normal throws. However, there may be partial inversion of these structures to create the antiformal structure on the NW side of the section. The post kinematic section lies on an erosional unconformity and onlaps significant relief across the section. Author: Rob Butler

Seismic Stratigraphy

Categories- Reflection Character Analysis

Mark Onlap

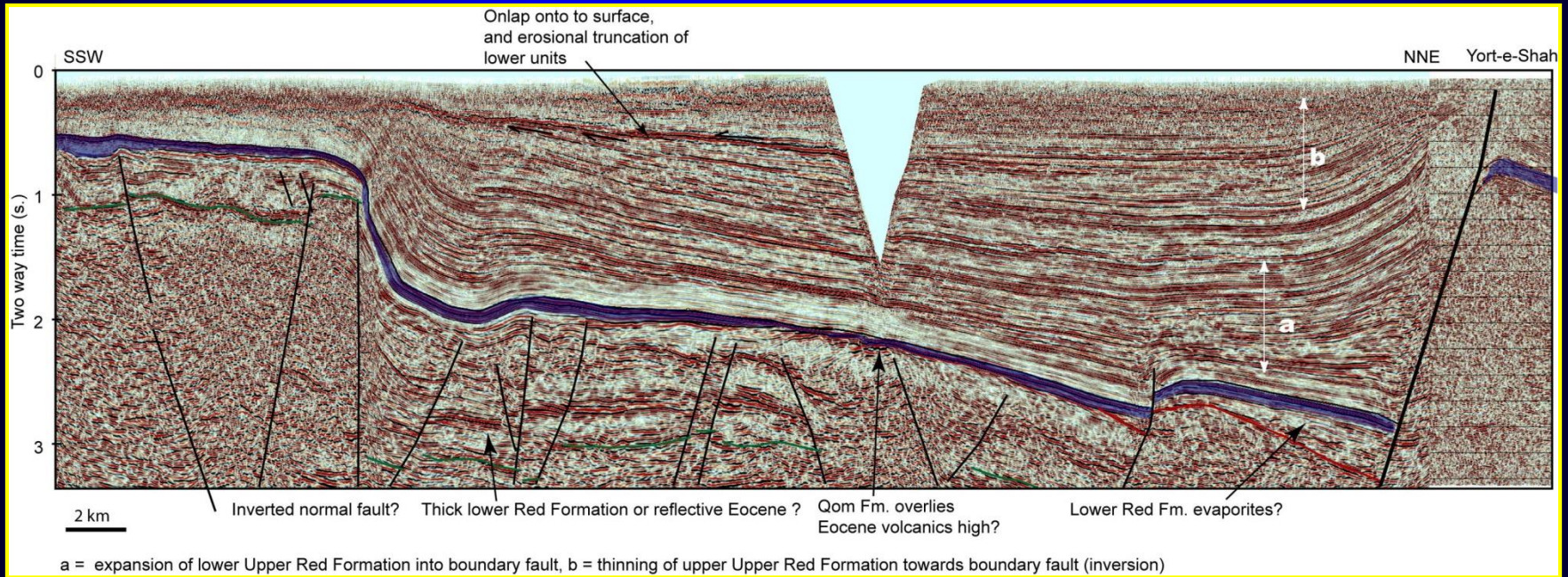


Profile across part of the Central Basin, Iran, NE of the city of Qom. Image from Morley et al. (in press, 2009) Structural development of a major Late Cenozoic basin and transpressional belt in Central Iran: the Central Basin in the Qom-Saveh area. Author: Chris Morley

Seismic Stratigraphy

Categories- Reflection Character Analysis

Onlap



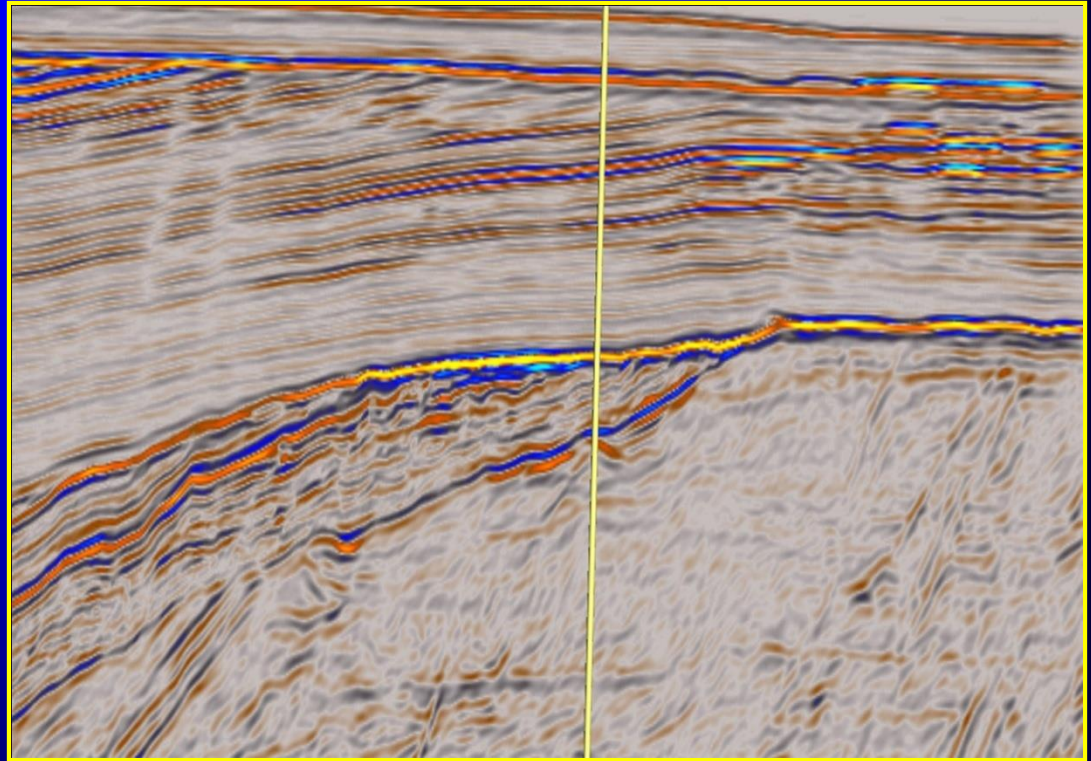
Seismic Stratigraphy

Categories- Reflection Character Analysis

Mark

1-Onlap

2- Erosional Truncation

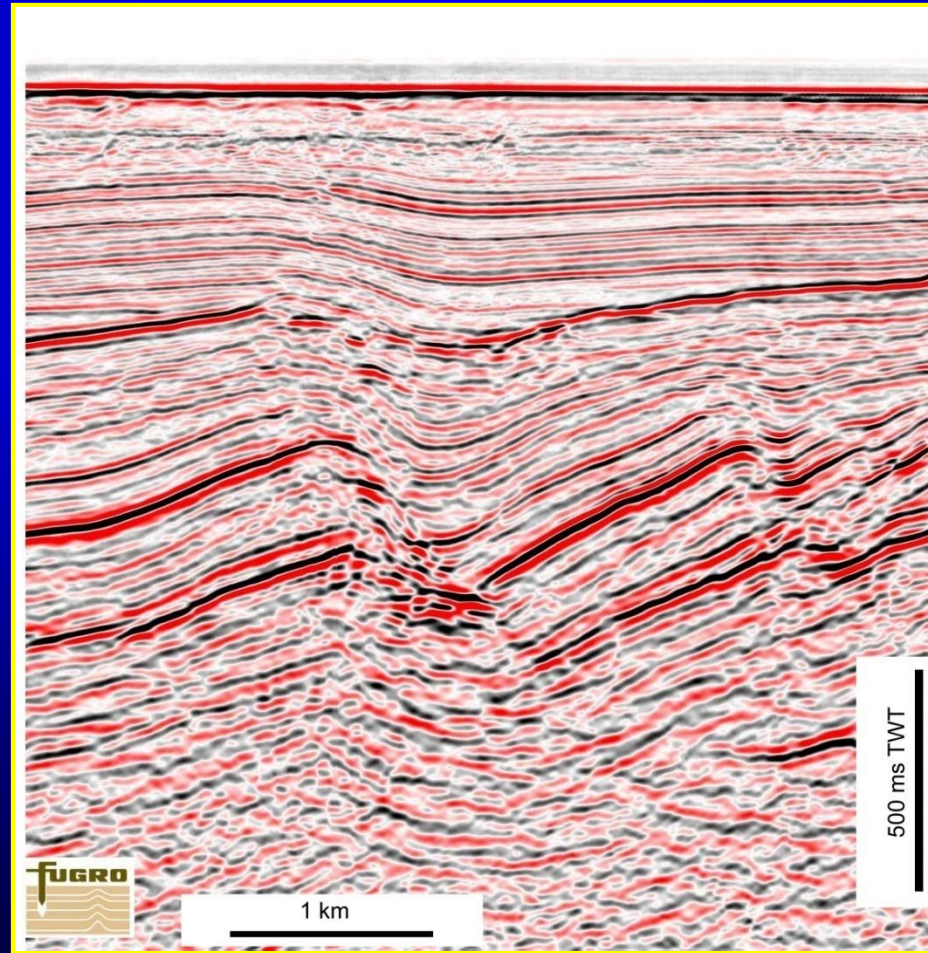


A dipline (see the associated regional project for location) with a well location marked. Note the angular truncation and erosion of the carbonates below the major unconformity associated with the karstification of the carbonates. This erosion formed a distinct penenplain, that is readily traced across basement rocks (right) into the karsted carbonates at the well location.

Seismic Stratigraphy

Categories- Reflection Character Analysis

Mark Onlap

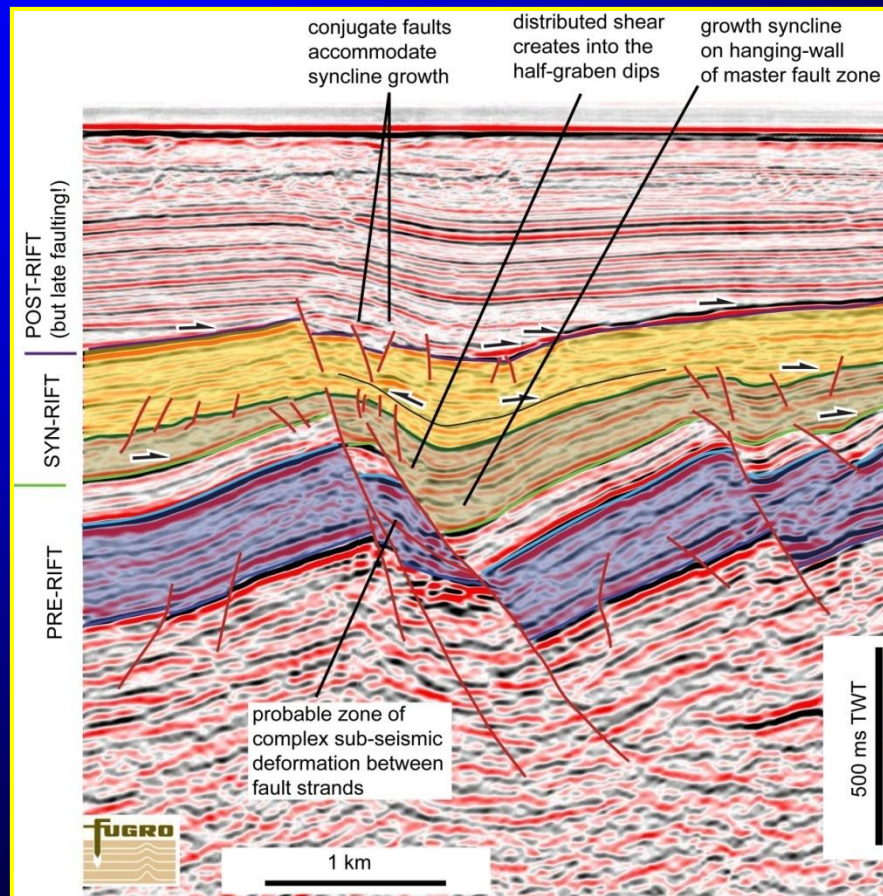


Seismic Stratigraphy

Categories- Reflection Character Analysis

Onlap

An interpretation of the fault geometry and basin fill in part of the Inner Moray Firth. This interpretation was done using 2D seismic data alone (see related regional line) and without reference to external data or models. The arrows denote stratal terminations (onlap).



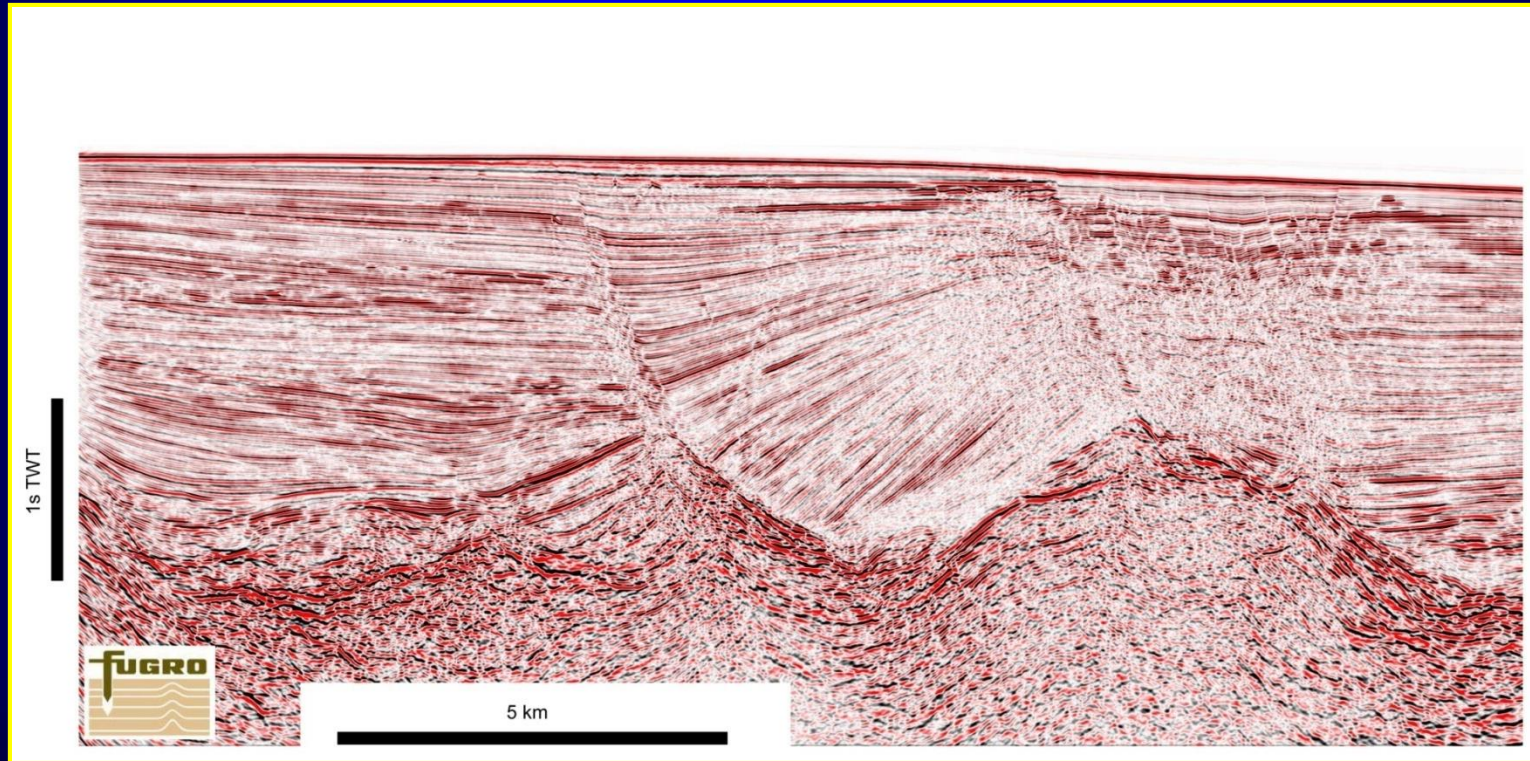
Seismic Stratigraphy

Categories- Reflection Character Analysis

Mark

1-Onlap

2- Erosional Truncation



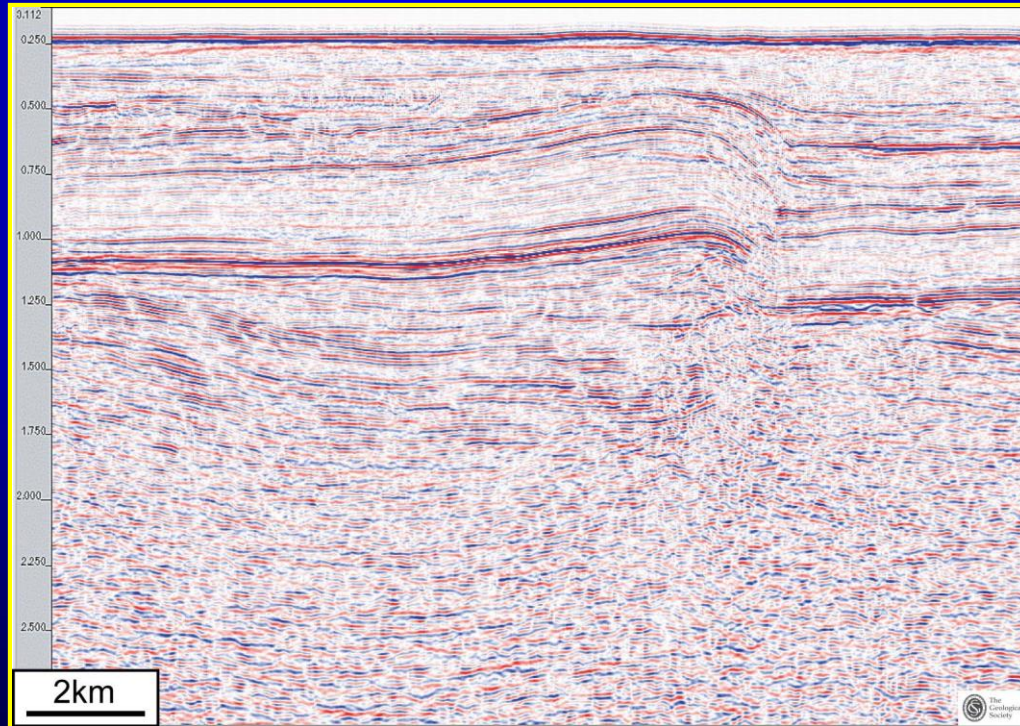
Seismic Stratigraphy

Categories- Reflection Character Analysis

Mark

1-Onlap

2- Erosional Truncation

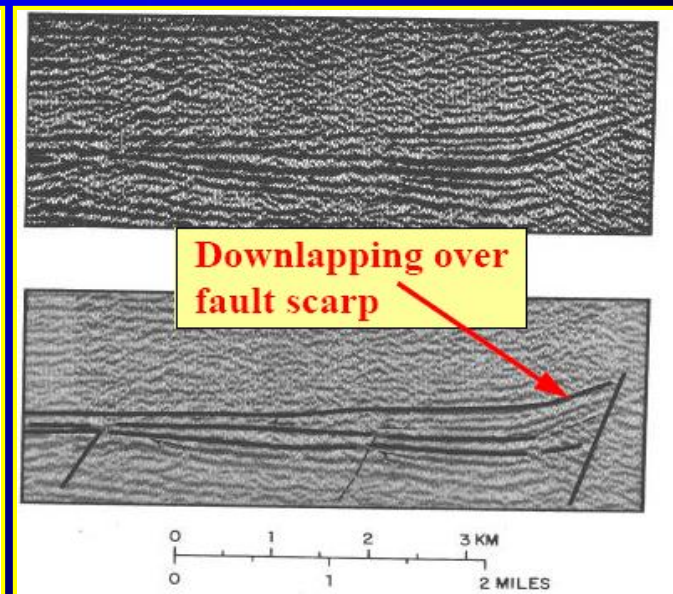
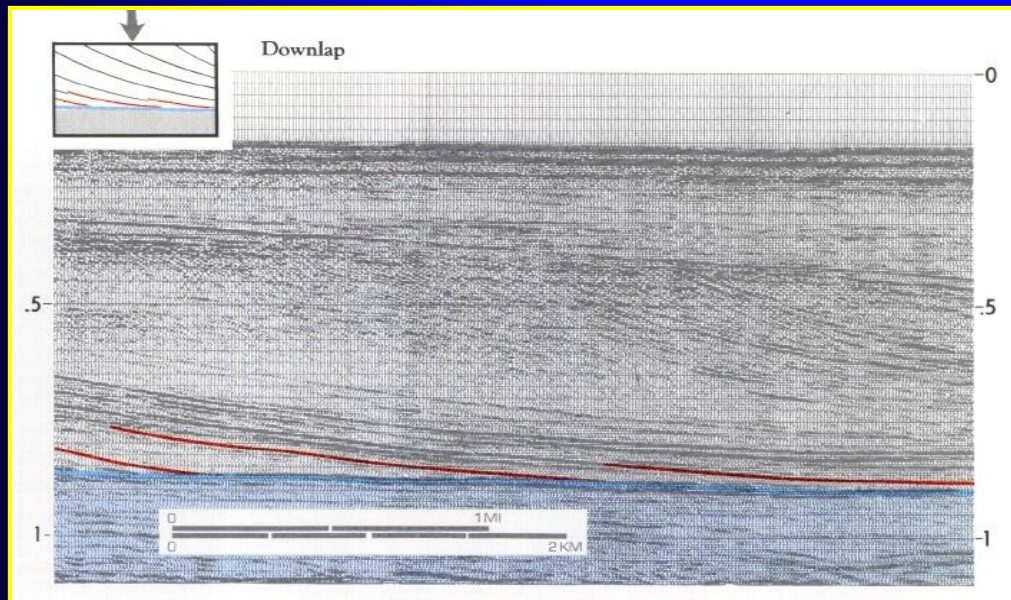


Seismic Stratigraphy

Categories- Reflection Character Analysis

Downlap (Lower Boundaries)

Seismic reflection of inclined strata terminate downdip against an inclined or horizontal surface



Surfaces are present at the base of prograding packages. They are commonly associated with maximum flooding surfaces produced by a rise in relative sea level

Seismic Stratigraphy

Categories- Reflection Character Analysis

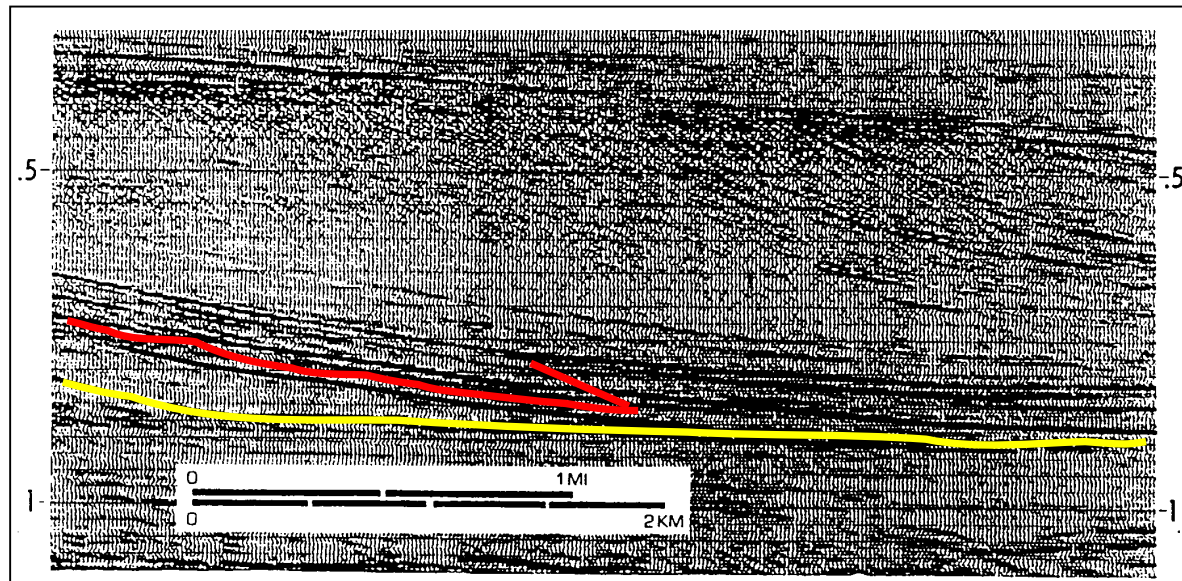
Downlap

- 1- Distal downlap
- 2- False downlap
- 3- Shelf downlap
- 4- Basin downlap
- 5- Opposite (local) downlap
- 6- Apparent downlap

Seismic Stratigraphy

Categories- Reflection Character Analysis

Mark Downlap (Lower Boundaries)



Seismic Stratigraphy

Categories

Seismic stratigraphy is divided into two main categories:

- **Reflection- character analysis**
- **Seismic facies analysis**

Seismic Stratigraphy

Categories- Seismic Facies Analysis

Why Seismic facies analysis

- Estimating deposition environment using the character of the seismic reflections.
- Understand depositional history.
- Locate and predict potential hydrocarbon reservoir and stratigraphic traps.

Seismic Stratigraphy

Categories-Seismic Facies Analysis

Seismic facies

It is the group of reflections bounded by top and base boundaries.

Seismic parameters used for facies detection are

- 1)-Reflection configuration
- 2)-Reflection amplitude
- 3)-Frequency
- 4)-Continuity
- 5)-Interval velocity

Seismic Stratigraphy

Categories-Seismic Facies Analysis

Facies Parameters	Geologic Interpretation
1- Reflection Configuration a) Internal config forms b) External config forms	•Bedding patterns •Depositional processes •Fluid contacts
2- Reflection Continuity	•Bedding continuity •Depositional processes
3- Reflection Amplitude	•AI contrast •Bed thickness (tuning) •Fluid content
4- Reflection Frequency	•Bed thickness •Fluid content
5- Interval Velocity	•Lithology •estimation •Porosity estimation •Fluid content •Pressure

Seismic Stratigraphy

Categories-Seismic Facies Analysis

1- Reflection Configuration

Internal & External Forms Configurations

The overall geometry of a stratigraphic, or seismic unit, consists of the internal form and the external reflection configuration of the unit. Both must be described to understand the geometric interrelation and depositional setting of the units.

- Internal Forms of Reflection Configuration (Filling pattern)

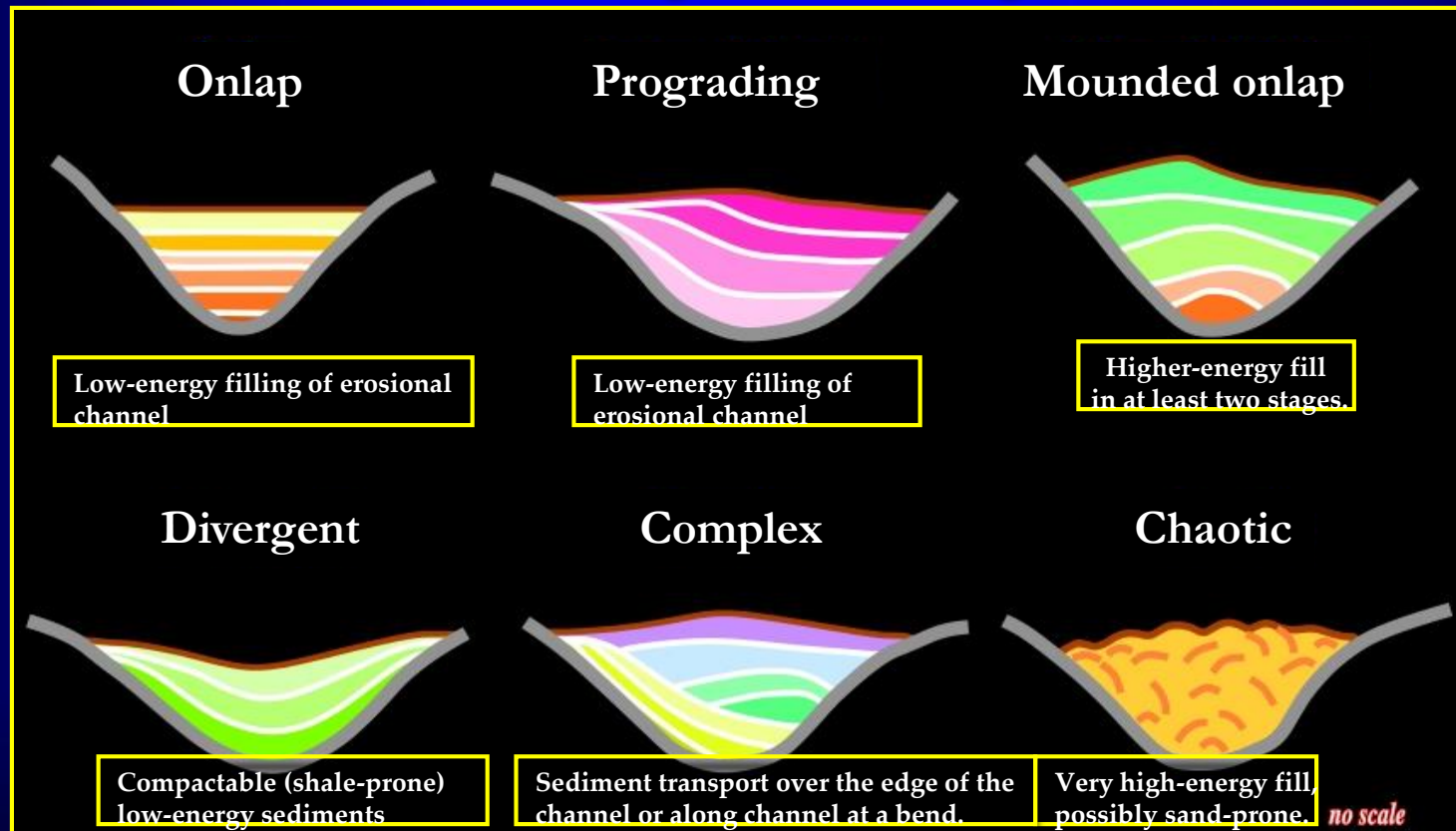
- 1-Onlap
- 2-Prograding
- 3-Mounded onlap
- 4-Divergent
- 5-Complex
- 6-Chaotic

Seismic Stratigraphy

Categories-Seismic Facies Analysis

1- Reflection Configuration

Internal Reflection Configuration (Filling Pattern)

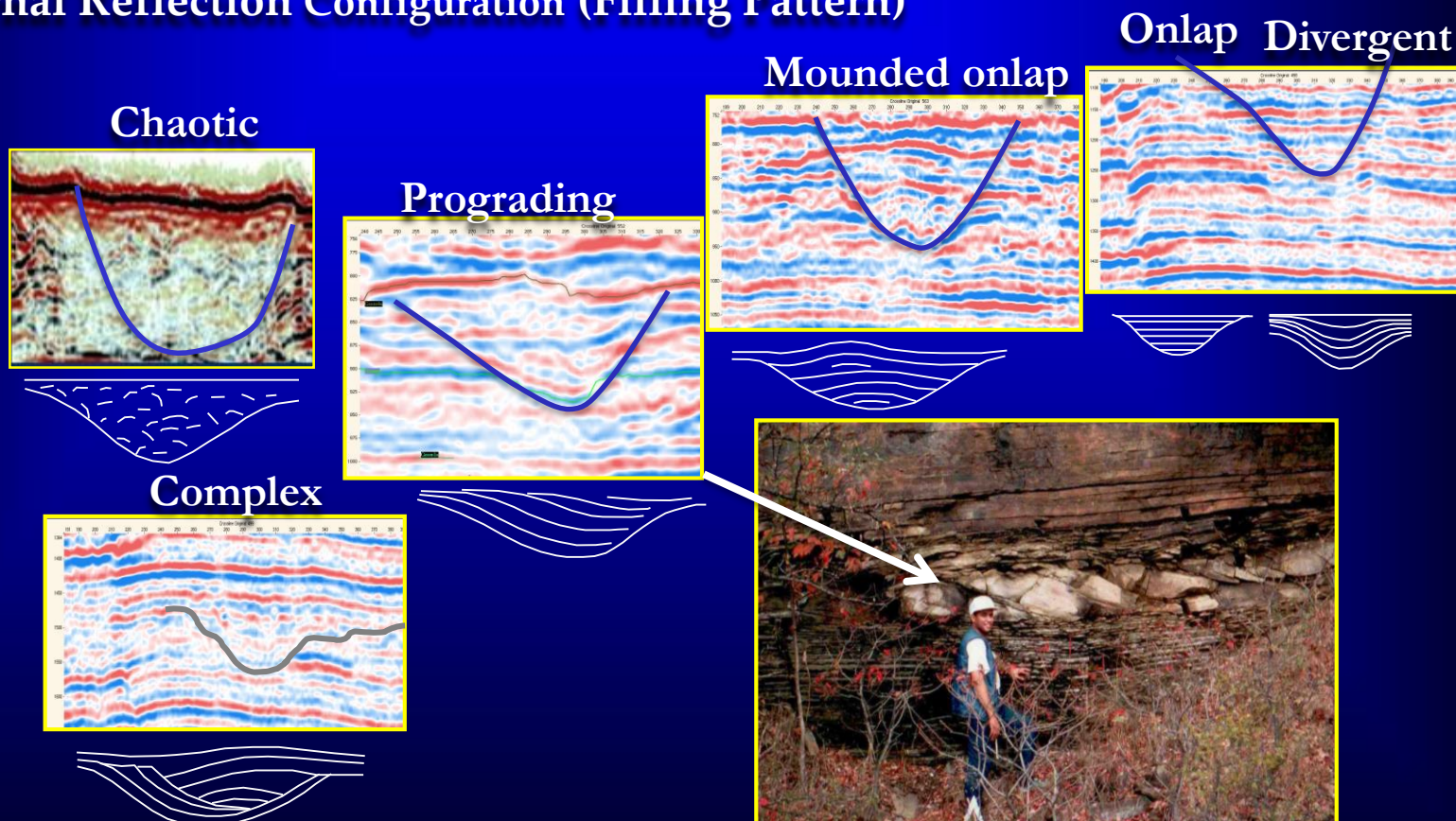


2-Seismic Stratigraphy

Categories-Seismic Facies Analysis

1- Reflection Configuration

Internal Reflection Configuration (Filling Pattern)

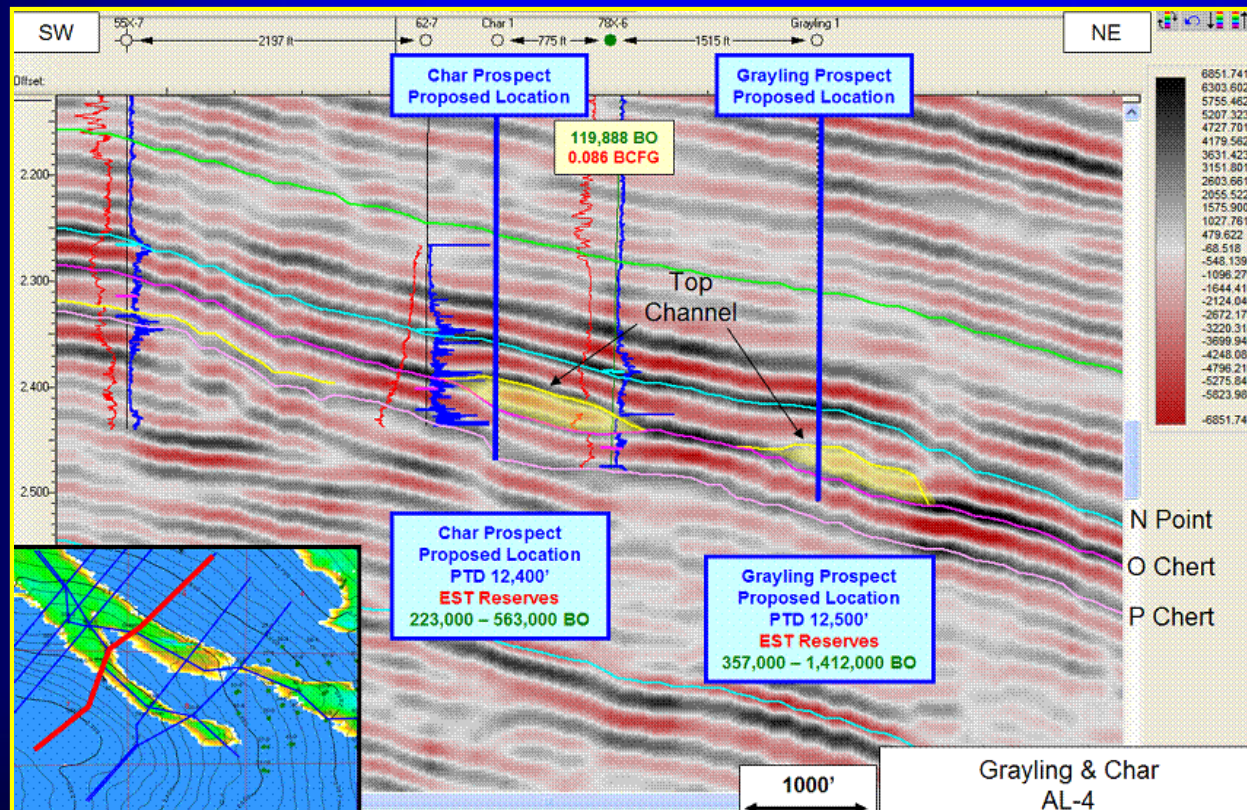


Seismic Stratigraphy

Categories-Seismic Facies Analysis

1- Reflection Configuration

Mounded onlap



Apparent Dip
relation to the
channel

Seismic Stratigraphy

Categories-Seismic Facies Analysis

1- Reflection Configuration

Internal & External Forms Configurations

The overall geometry of a stratigraphic, or seismic unit, consists of the internal form and the external reflection configuration of the unit. Both must be described to understand the geometric interrelation and depositional setting of the units.

- Internal Forms of Reflection Configuration (Filling pattern)

- 1-Onlap
- 2-Prograding
- 3-Mounded onlap
- 4-Divergent
- 5-Complex
- 6-Chaotic



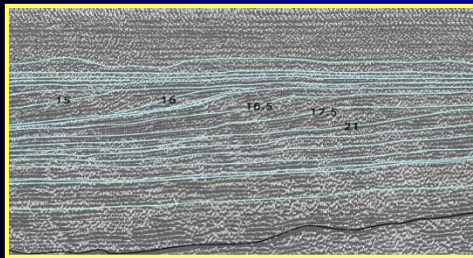
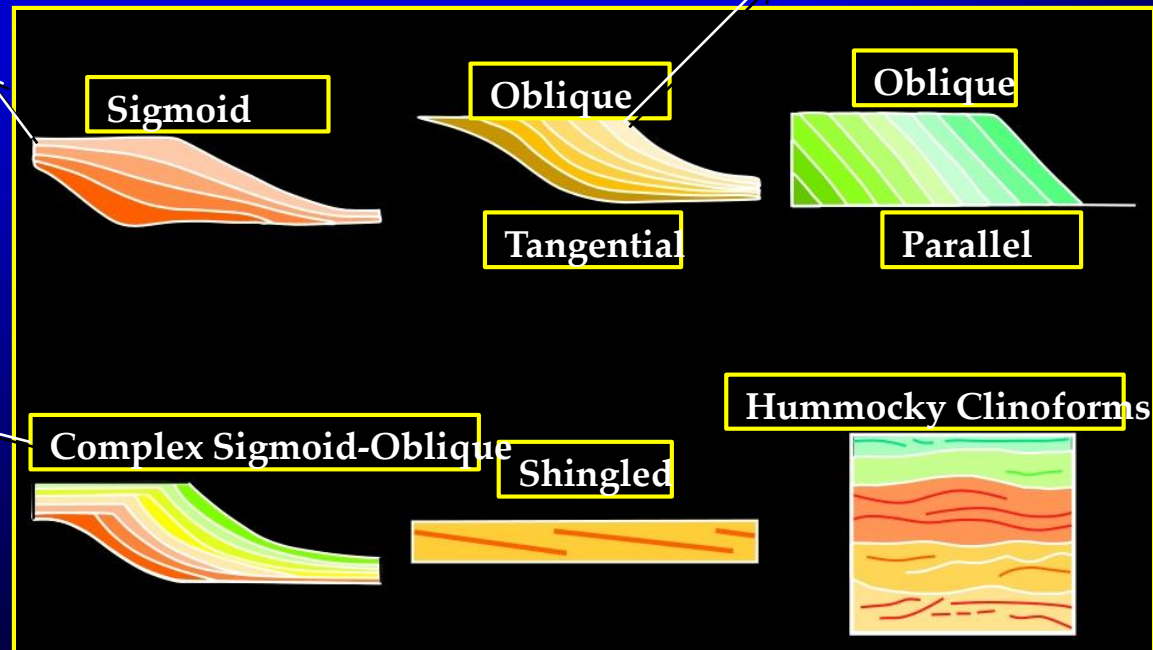
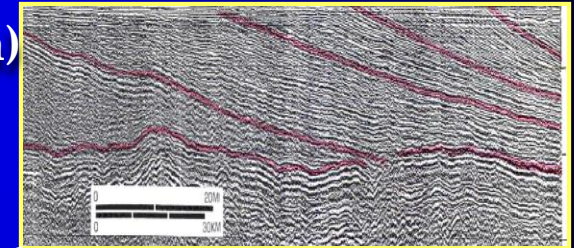
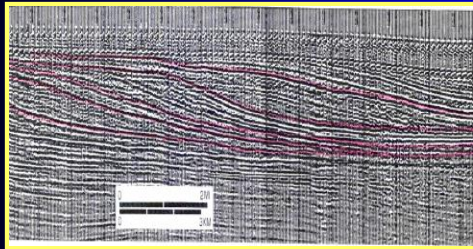
Seismic Stratigraphy

Categories-Seismic Facies Analysis

1- Reflection Configuration

Internal Reflection Configuration (Filling Pattern)

Prograding Pattern types



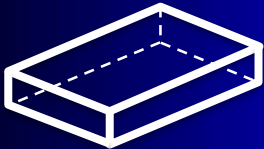
Seismic Stratigraphy

Categories-Seismic Facies Analysis

1- Reflection Configuration

External Reflection Configuration

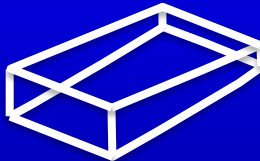
sheet



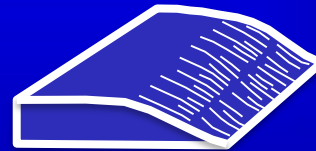
drape



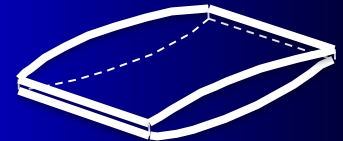
wedge



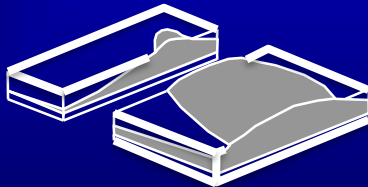
bank



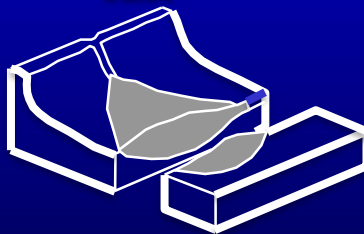
lens



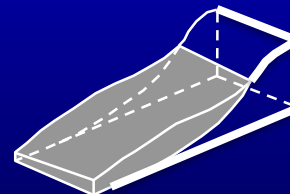
mound



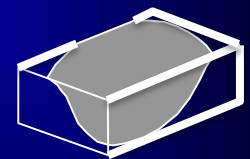
fan



front slope fill



channel fill



Trough fill

Basin fill

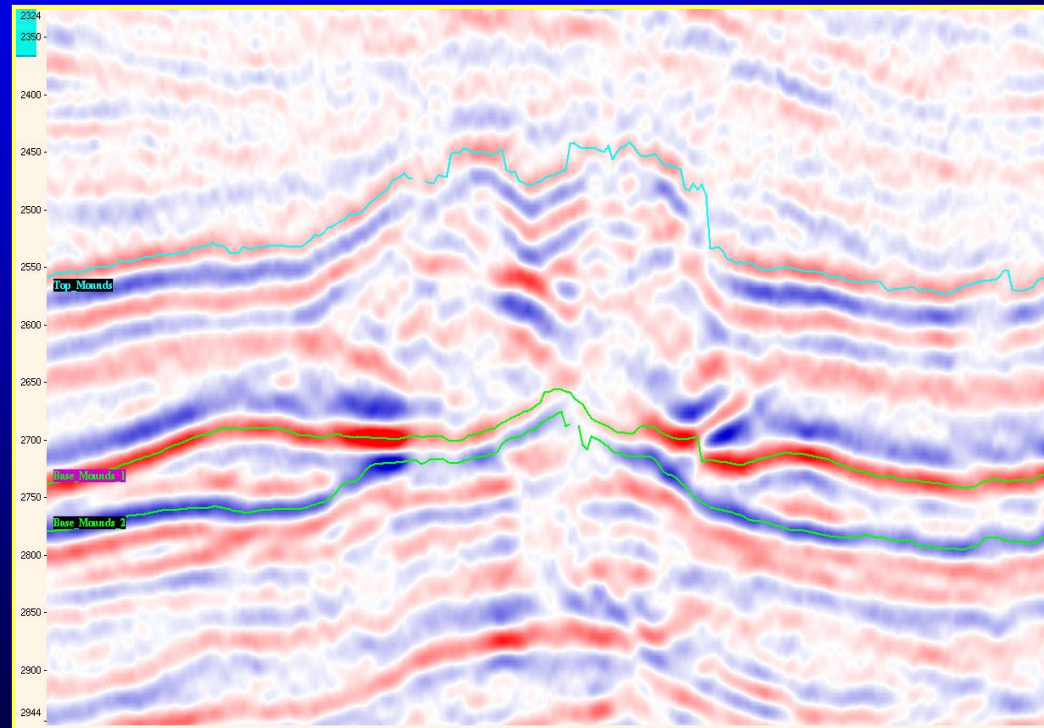
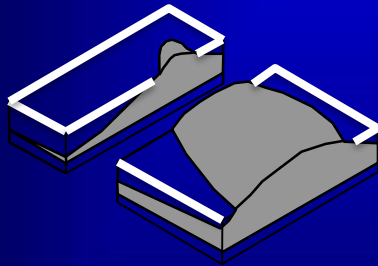
Seismic Stratigraphy

Categories-Seismic Facies Analysis

1- Reflection Configuration

External forms of reflection configuration

Mound



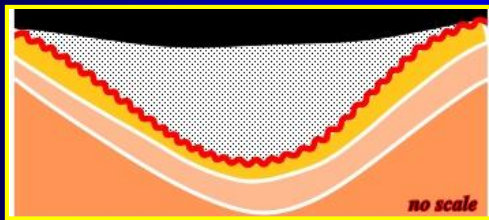
Seismic Stratigraphy

Categories-Seismic Facies Analysis

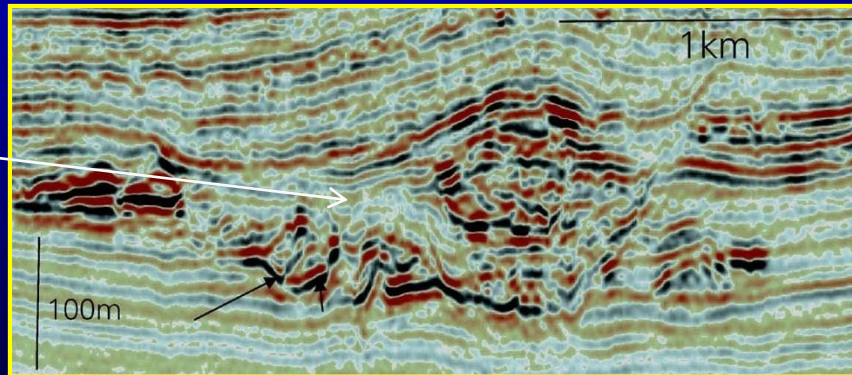
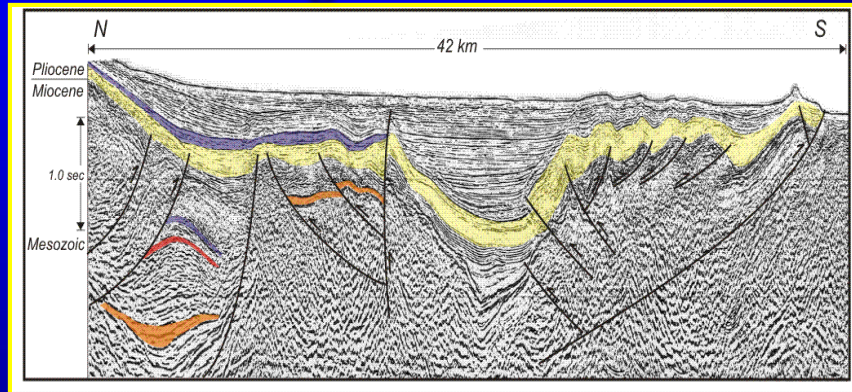
1- Reflection Configuration

External forms of reflection configuration

Trough Fill



Seismic example illustrating the complicated stratigraphy of a submarine slope valley fill with adjacent levee deposits. Image taken from Mayall et al., 2006.



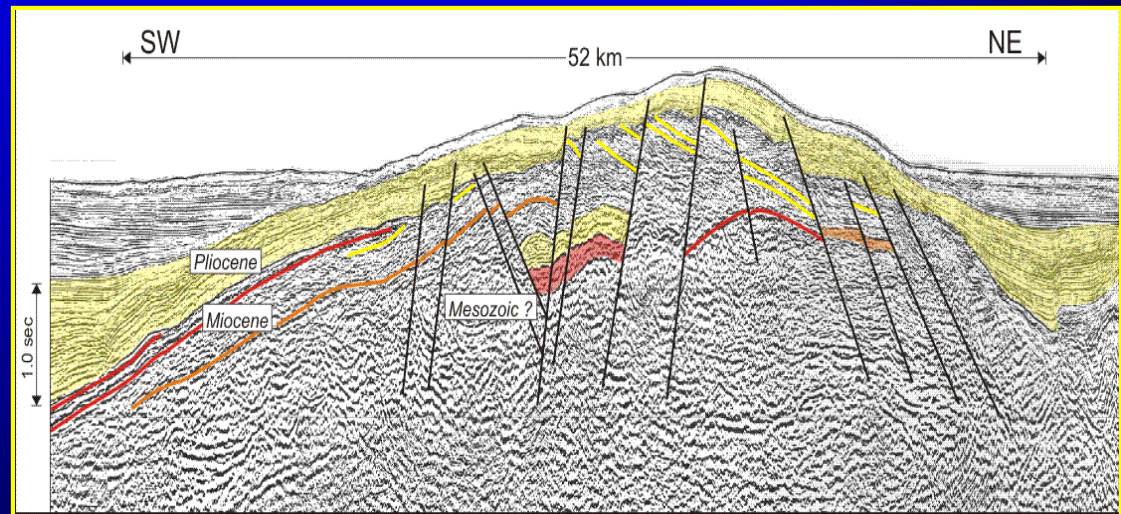
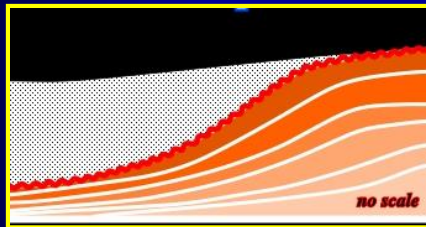
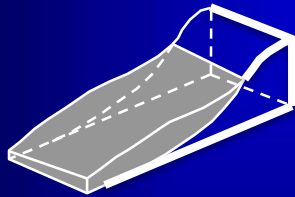
Seismic Stratigraphy

Categories-Seismic Facies Analysis

1- Reflection Configuration

External forms of reflection configuration

Front Slop Fill



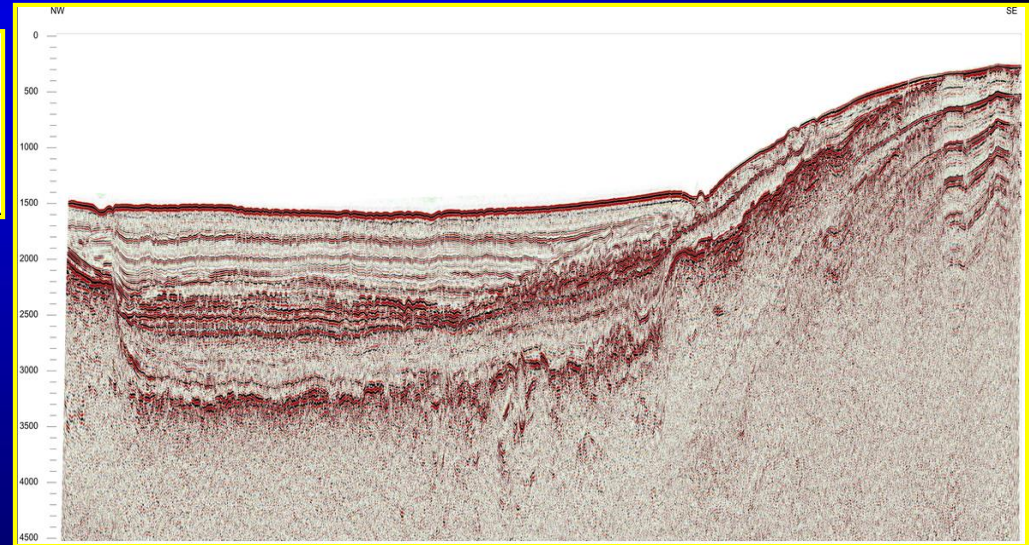
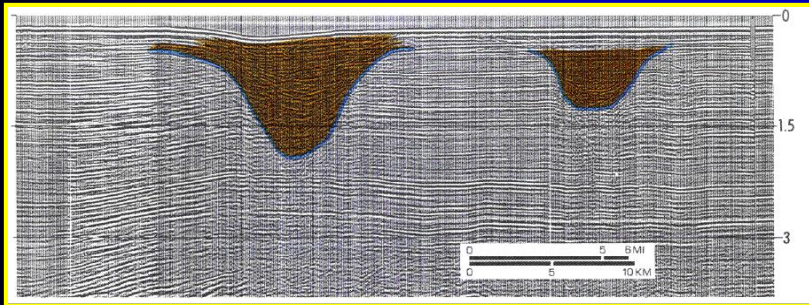
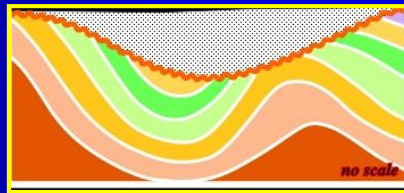
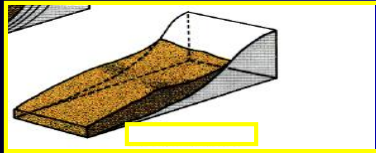
Seismic Stratigraphy

Categories-Seismic Facies Analysis

1- Reflection Configuration

External forms of reflection configuration

Basin Fill



This 2D seismic line (BGS1993_02_C) is aligned NW-SE across the Hatton Basin. Buried volcanic escarpments are imaged on both margins of the basin. Each has a relief of c. 1 second TWT. The escarpments are buried beneath the Tertiary sedimentary fill of the Hatton Basin, which thins towards the basin margins, onlapping the flanks.

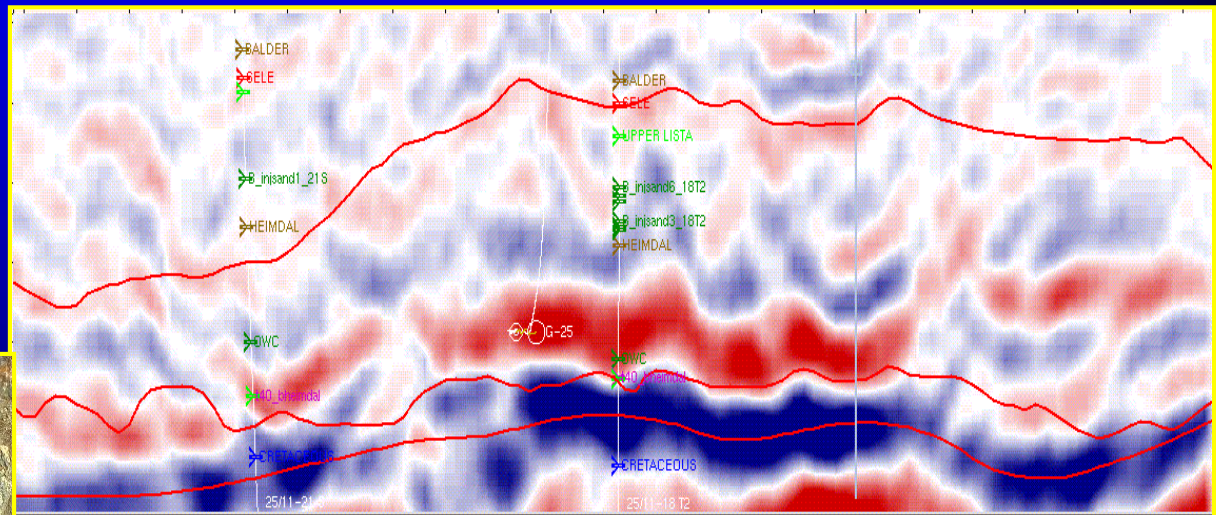
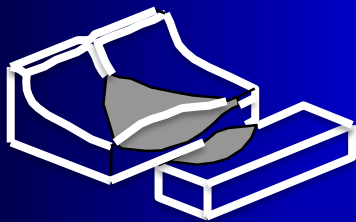
Seismic Stratigraphy

Categories-Seismic Facies Analysis

1- Reflection Configuration

External forms of reflection configuration

Fan



Seismic Stratigraphy

Categories-Seismic Facies Analysis

Classification: two types of “dry alluvial fan” and “wet alluvial fan”.

Type	dry alluvial fan	Wet alluvial fan
scale	small	large
gradient	steep	gentle
depositional process	main debris flow	debris flow, Flash flood

Seismic Stratigraphy

Categories-Seismic Facies Analysis

Feeder canyon

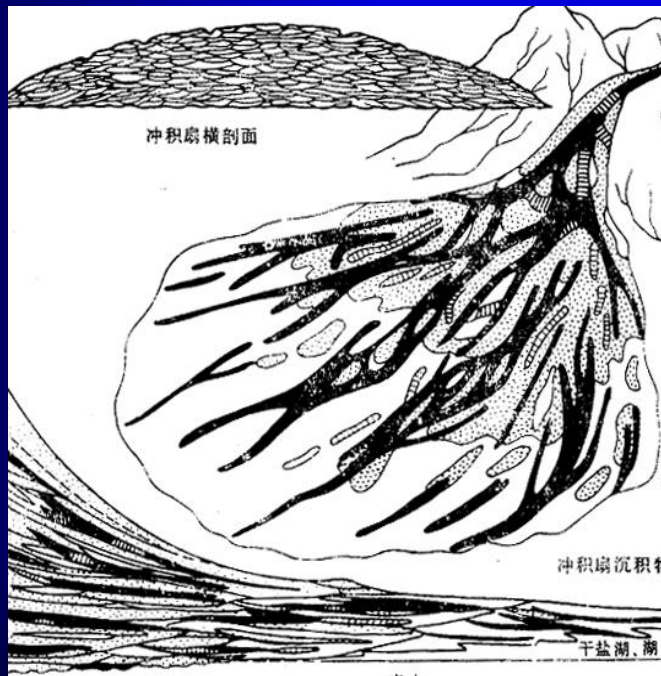


Badwater Fan, Death Valley- Oblique airphoto looking SSW. Note dendritic pattern across fan surface. Road encircling fan provides scale.

Seismic Stratigraphy

Categories-Seismic Facies Analysis

- **In plane:** presents fan-shaped or linguiform. Its radius varied from several 10 meter to 100 kilometer.
- **In the longitudinal profile:** concave downward; the Depositional gradients in the piedmont zone are steep up to 30° in marginal scree. Then gradually decreases far-away valley mouth.
- **In the transverse profile:** lentoid.

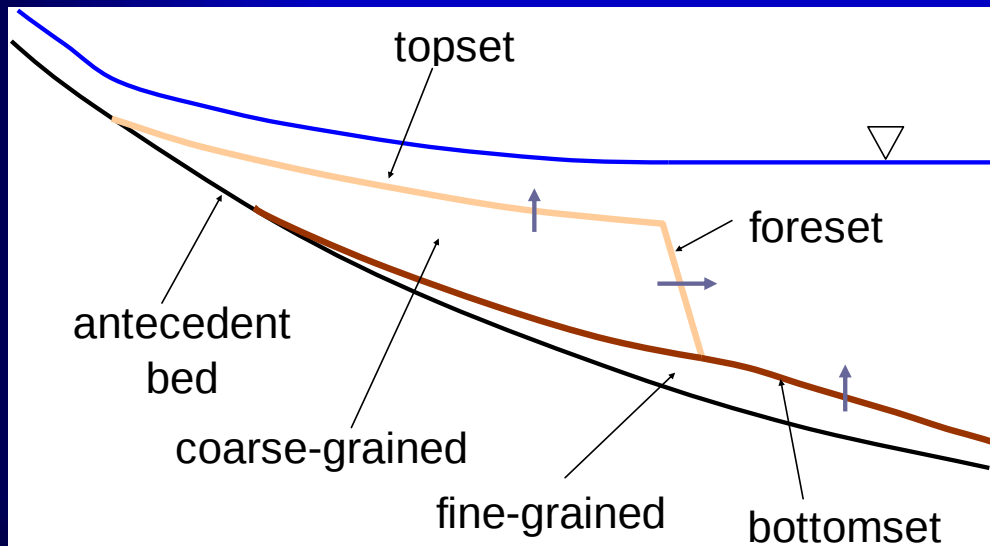


Seismic Stratigraphy

Categories-Seismic Facies Analysis

DEPOSITIONAL STRUCTURE OF FAN-DELTAS

The deposits of fan-deltas can be divided into three zones: a coarse-grained aggradational topset emplaced by fluvial deposition, a coarse-grained progradational foreset emplaced by avalanching and a fine-grained aggradational bottomset emplaced by plunging turbidity currents or rain from surface plumes. Subsidence may limit or stop progradation.



The foreset may be at or near the angle of repose (in which case it is called a Gilbert delta), but is usually well below this angle. In a sand-bed stream, the topset and foreset are sandy and the bottomset is muddy. In a gravel-bed stream the topset and foreset are often composed of gravel and coarse sand, and the bottomset of finer sand and mud.

Seismic Stratigraphy

Categories-Seismic Facies Analysis

A FAN-DELTA CREATED BY A DEBRIS FLOW EVENT

A combination of debris flows and sheet flows
associated with the Vargas Disaster, Venezuela, 1999
destroyed

the town of
Carmen de
Uria.



March, 1999



December, 1999

Images courtesy José Lopez, Universidad Central de Venezuela, Venezuela.

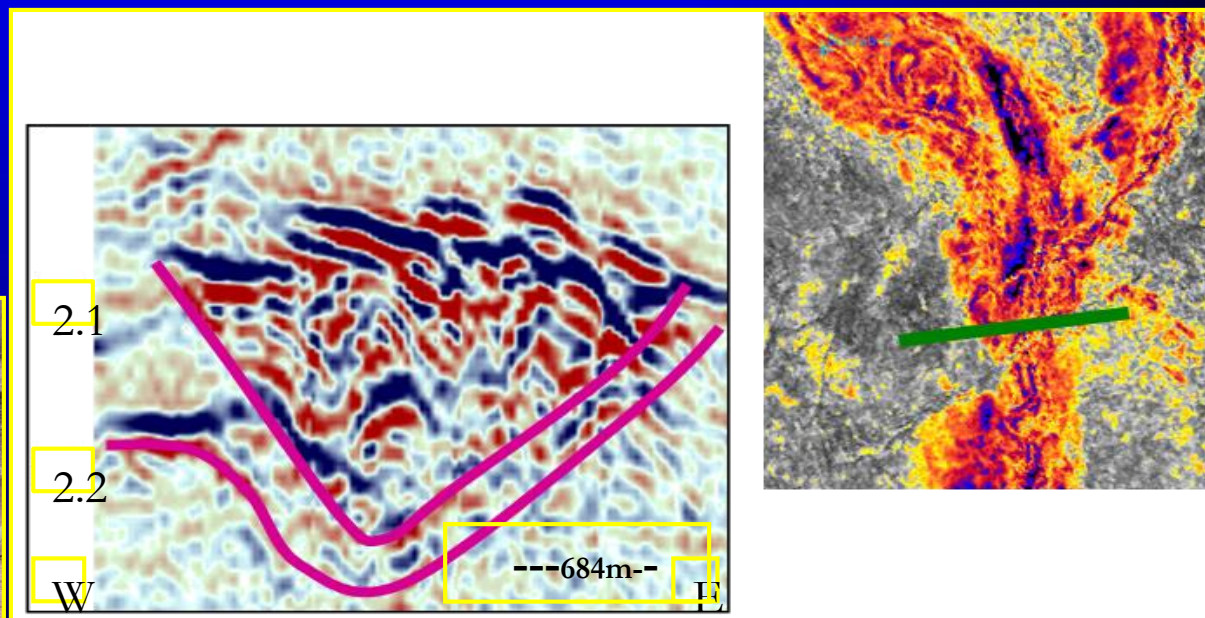
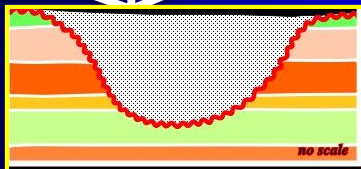
Seismic Stratigraphy

Categories-Seismic Facies Analysis

1- Reflection Configuration

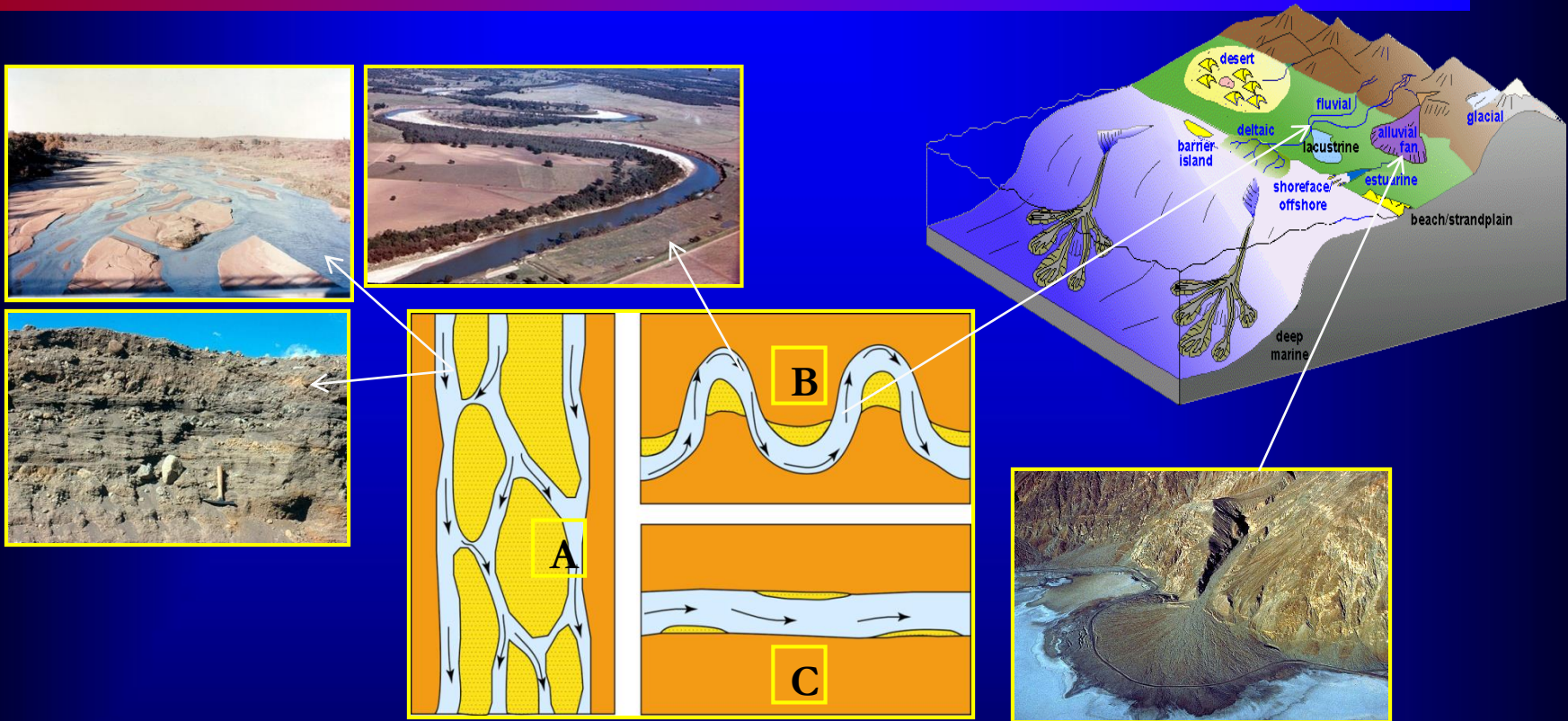
External forms of reflection configuration

Channel fill



Seismic Stratigraphy

Categories-Seismic Facies Analysis

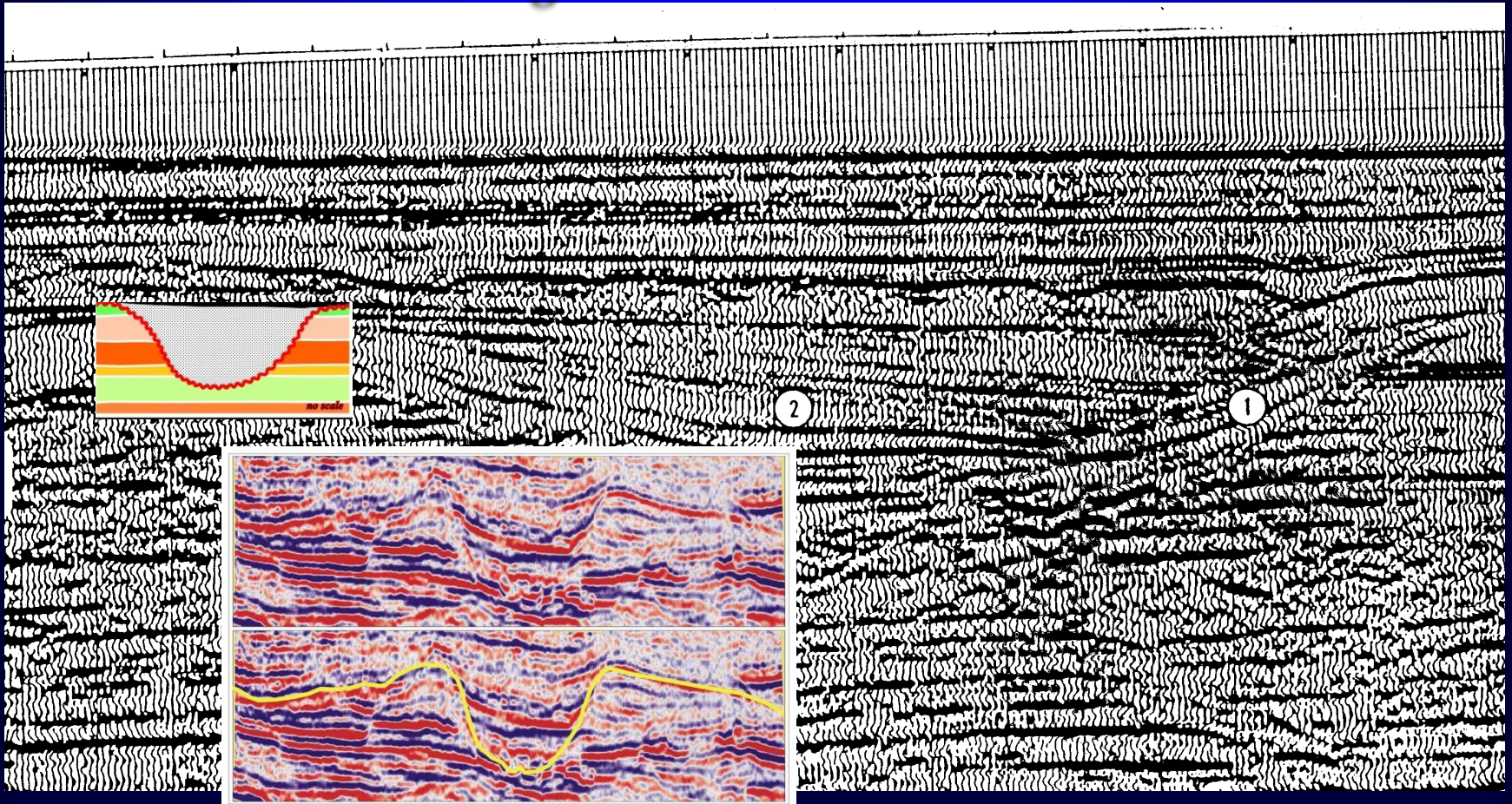


- A: Braided (low sinuosity, multi-channel stream)
B: Meandering (high sinuosity, single channel stream)
C: Straight (low sinuosity, single channel stream)

Seismic Stratigraphy

Categories-Seismic Facies Analysis

1- Reflection Configuration



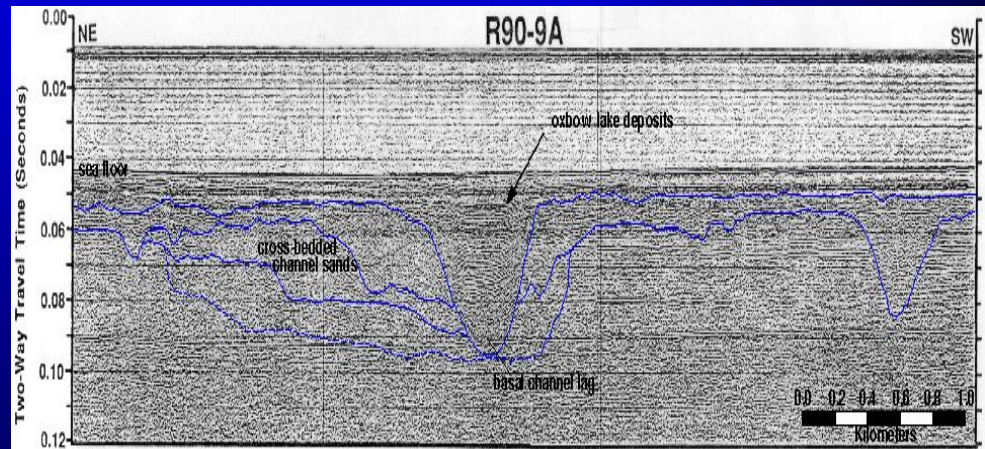
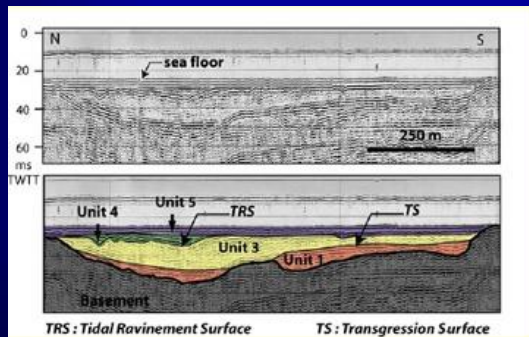
Seismic Stratigraphy

Categories-Seismic Facies Analysis

1- Reflection Configuration

External forms of reflection configuration

Incised Valley System



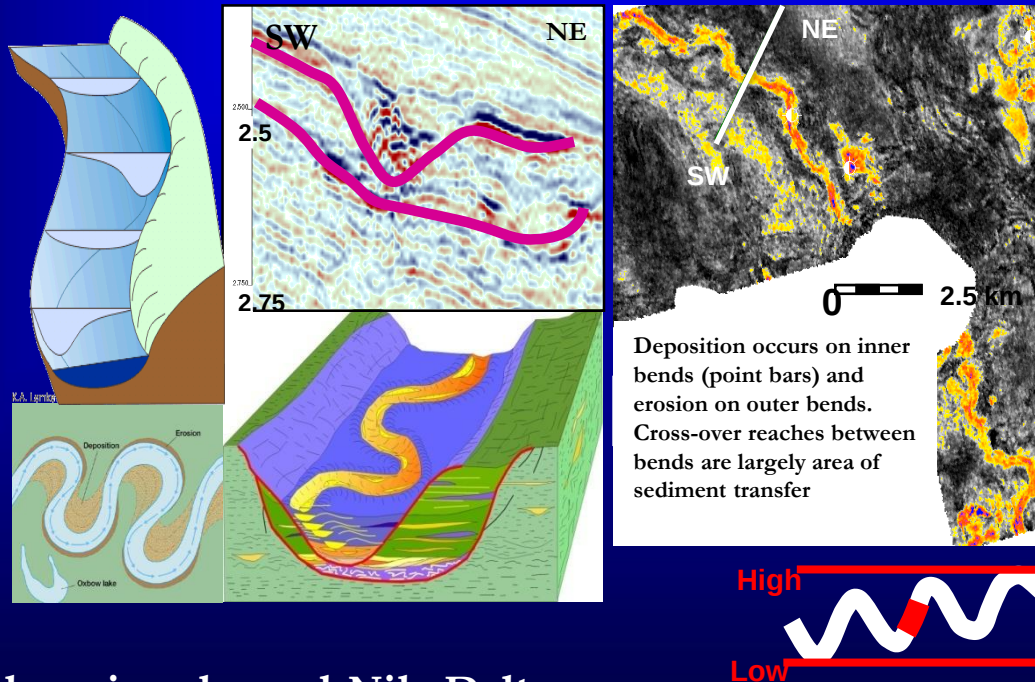
Seismic Stratigraphy

Seismic Facies Analysis

1- Reflection Configuration

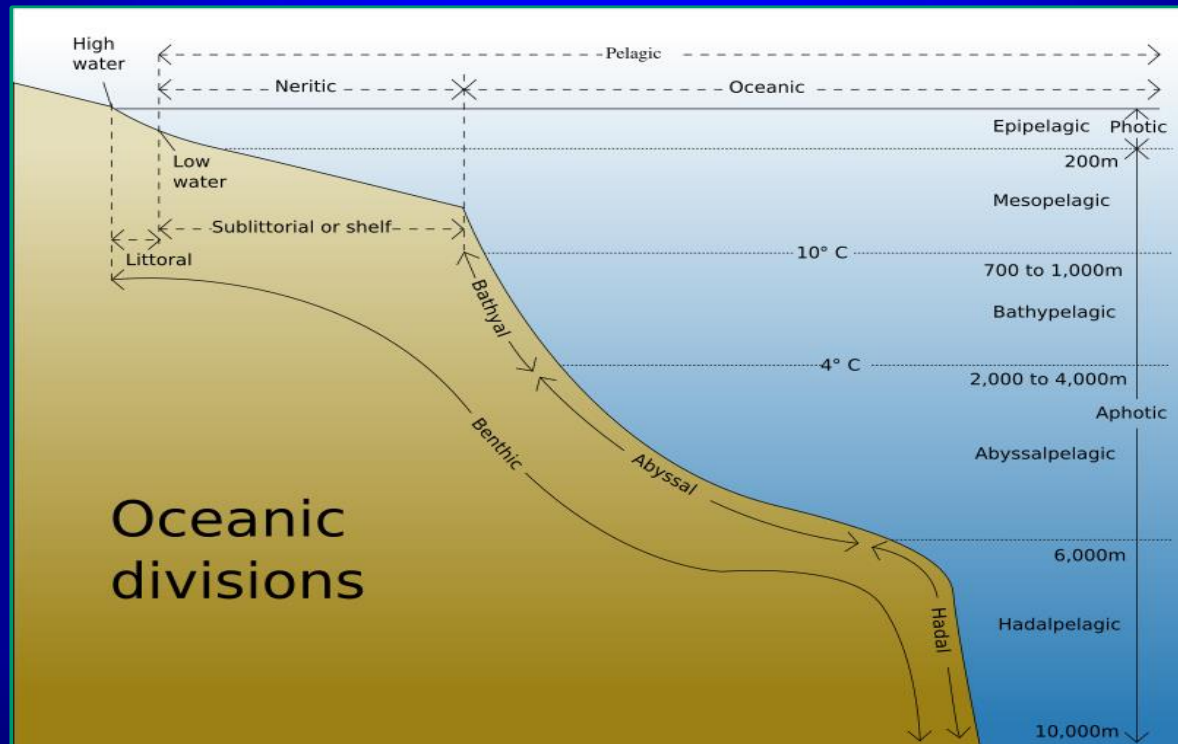
External forms of reflection configuration

Submarine Channel



Pliocene submarine channel-Nile Delta

Pelagic Environment



Pelagic zone

Any water in a sea or lake that is not close to the bottom or near to the shore can be said to be in the pelagic zone. The word *pelagic* comes from the Greek πέλαιος or *pélagos*, which means "open sea". The pelagic zone can be thought of in terms of an imaginary cylinder or water column that goes from the surface of the sea almost to the bottom. Conditions change deeper down the water column; the pressure increases, the temperature drops and there is less light. Depending on the depth, the water column, rather like the Earth's atmosphere can be divided into different layers.

Pelagic Environment

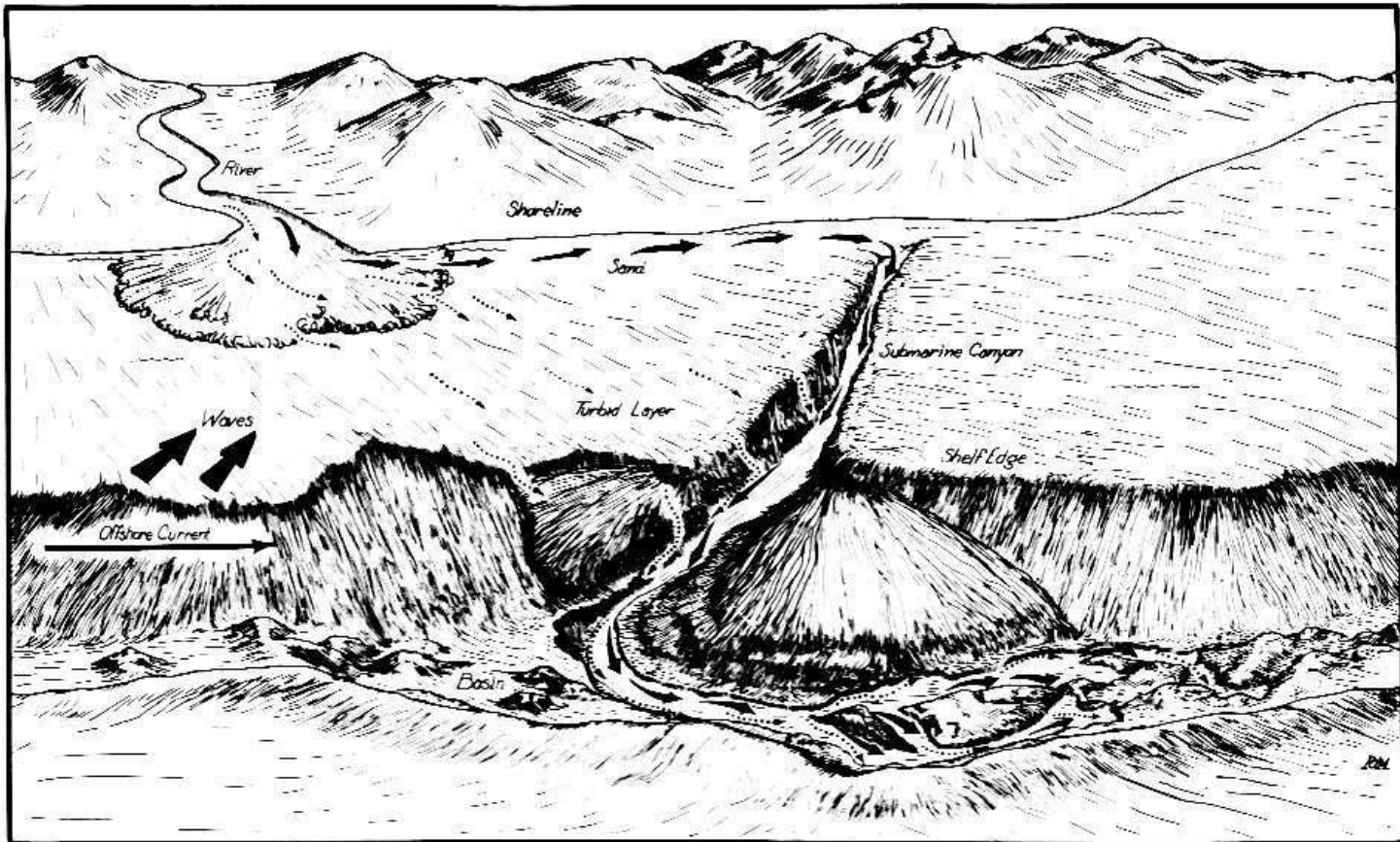
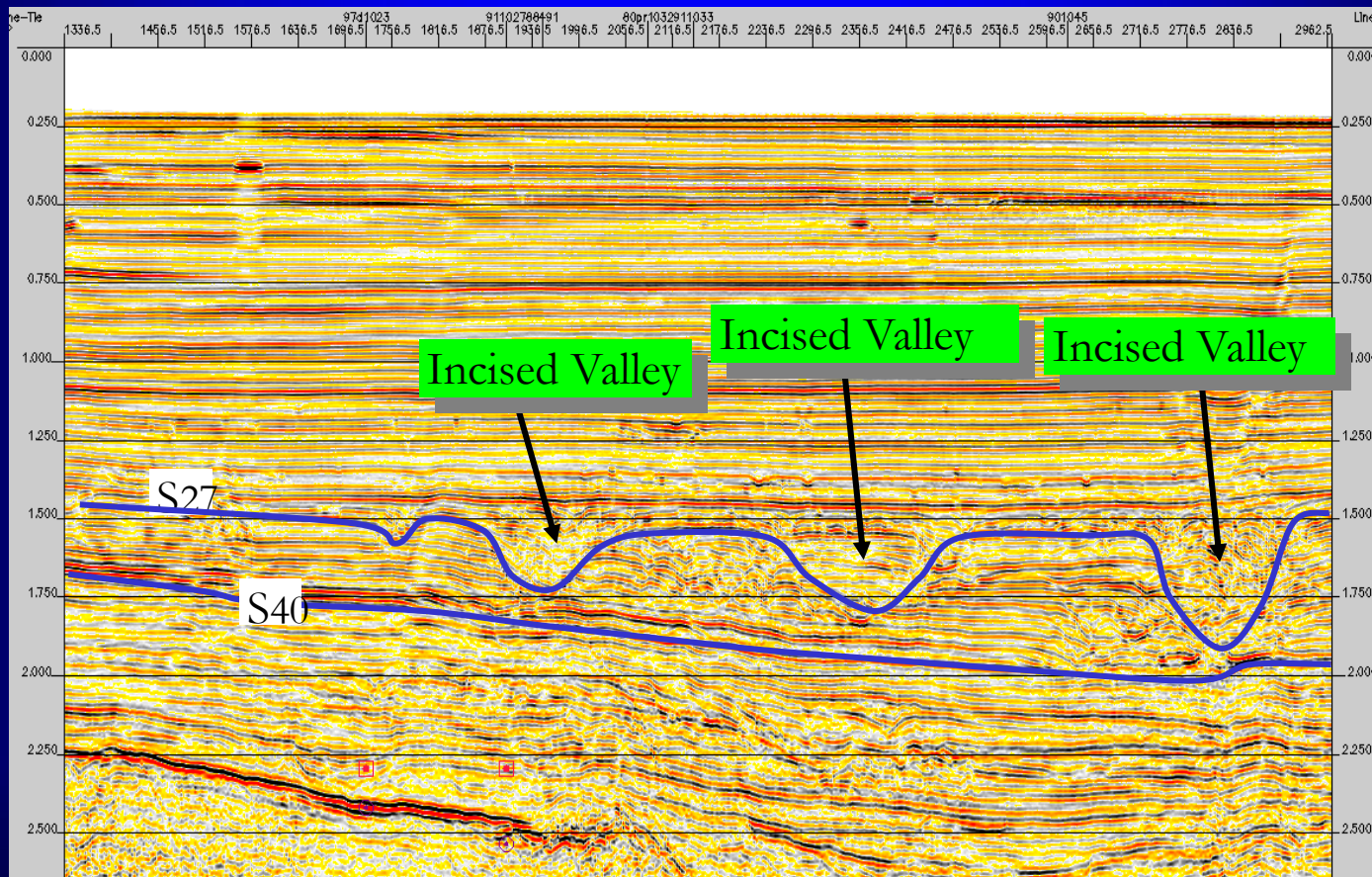


Fig. 636. Schematic representation of the routes of transportation of sand (solid arrow) and mud (dotted arrow) from river mouth to deep-sea basin floor. (After Moore 1969)

Pelagic Environment



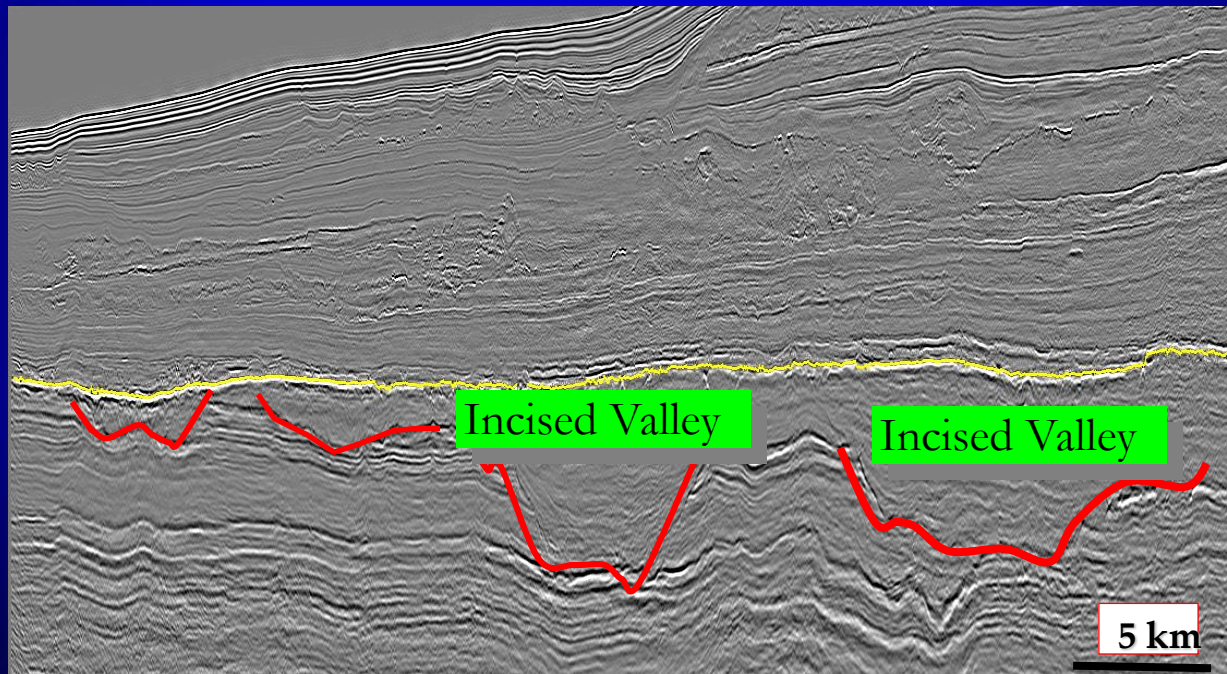
Seismic Stratigraphy

Categories-Seismic Facies Analysis

1- Reflection Configuration

External forms of reflection configuration

Incised Valley System

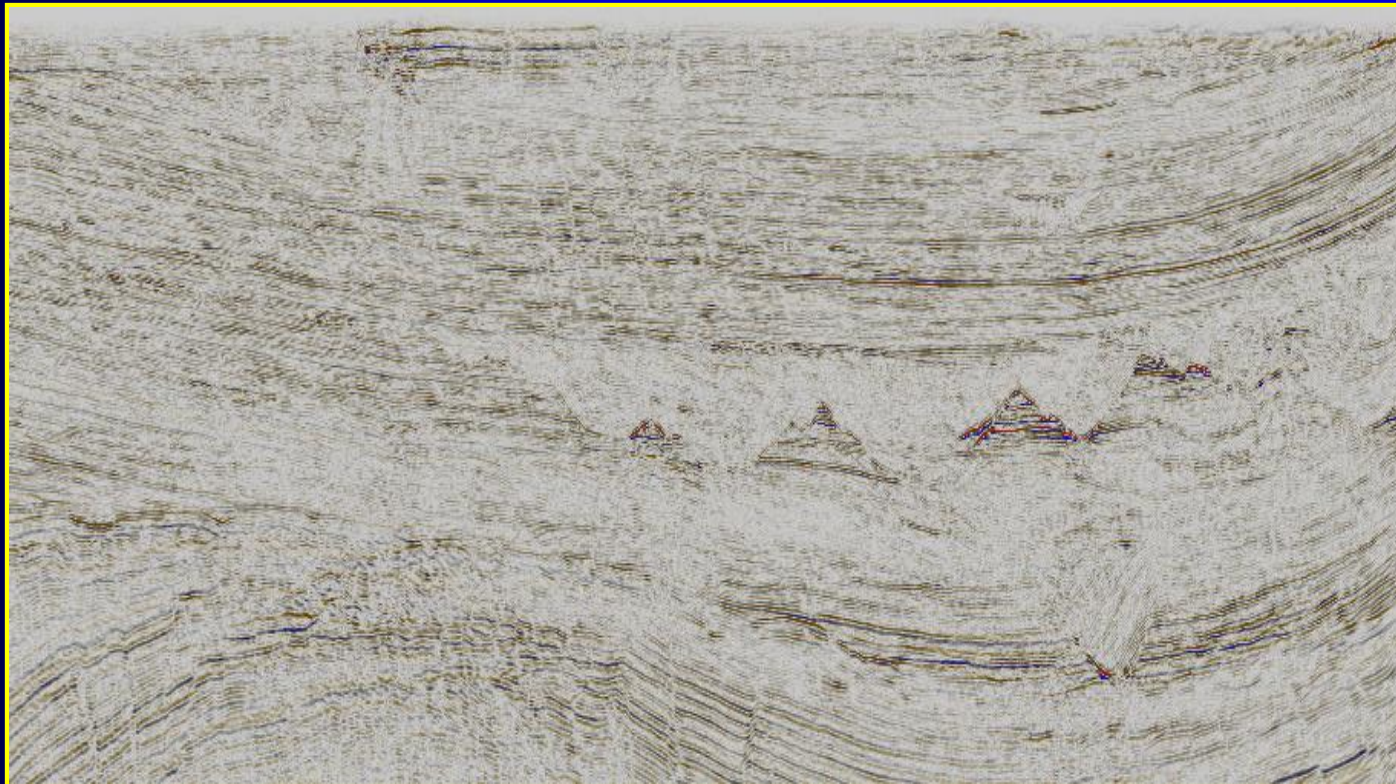


Incised Canyons sourcing sediment down slope Off shore Mediterranean

Seismic Stratigraphy

Categories-Seismic Facies Analysis

Mark **Incised Valley System**



General Morphology

- Break point: the point separating continent shelf from continent slope, generally at a water depth of 200m. The
- continental slope shows an average inclination of 4°.
- **Submarine canyon**: deep valley on continental slope, with steep-walled V-shaped section.
- **Submarine fan**: Fan-shaped sediment body at the down end of submarine canyon.
- **Sea mount**: more than 1km in height above the average surface of sea bottom.
- **Abyssal hills**: less than 1km in height.
- Mid-ocean ridge: a broad mountainous belt.

General Morphology

- **Trench**: deep-sea graben, deeper than 6000m, at the foot of continental slope restricted to tectonic active regions.
- **CCD**(calcite compensation depth): a depth, below which
- calcite does not accumulate on the deep sea floor, generally 3800~4500m.

Sedimentation

- 1. Re-sedimentation: all the processes that move sediment downslope over the sea floor from shallower to deeper water and are driven by gravitational forces.
- 2. Normal bottom current: deep currents that erode, transport and deposit on sea floor, but are not driven by gravitational forces, such as internal waves and tides,
- canyon current and bottom current(contour current).
- 3. Setting: slow setting in the pelagic water column.

Submarine Fan

Sand Fan:

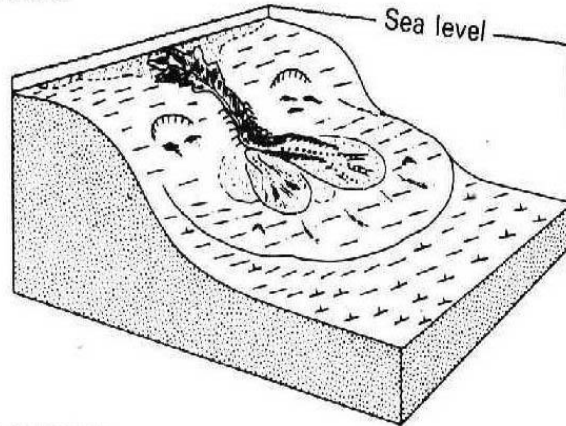
Radial fans, sandy, low-efficiency, canyon-fed. Radii: a few kilometers to a few hundred kilometers; Sediment thickness: less than 1km.

Mud Fan:

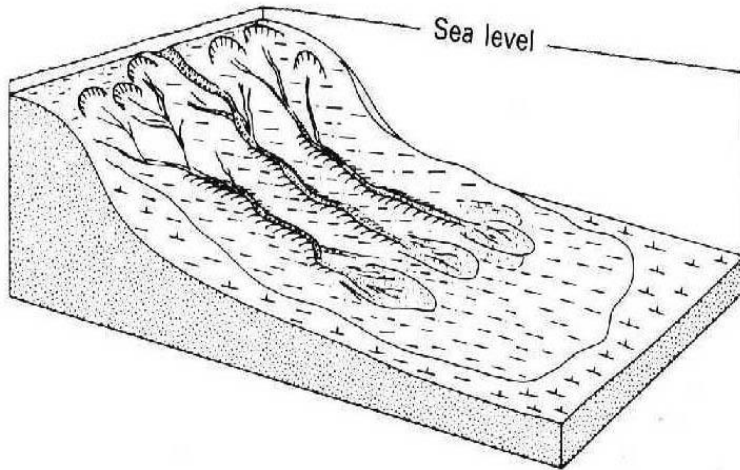
Elongate fans, muddy, high-efficiency, delta-fed, large and open-basin fans. Length: less than 5km~ more than 1000km; Sediment thickness: more than 10km.

Submarine Fan

A RADIAL



B ELONGATE



Radial Fan:

radius nkm ~n100 km,
thickness<1 km, rich in
sand.

Elongate fan:

radius 5km ~ >1000 km,
thickness > 10 km, rich in
mud, supplied by delta.

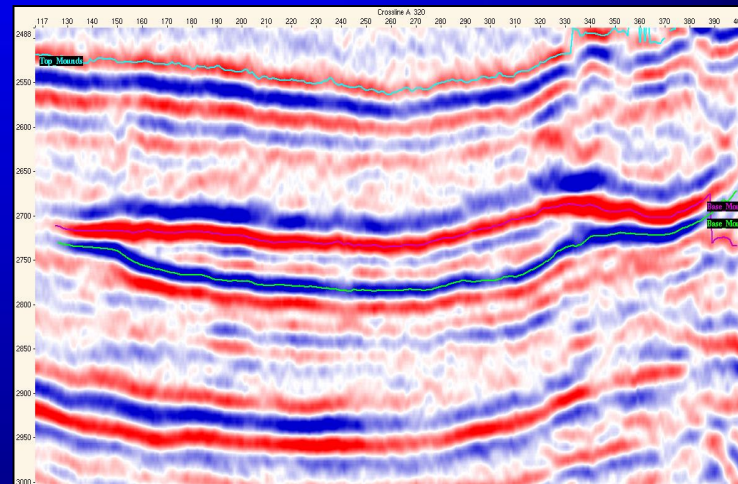
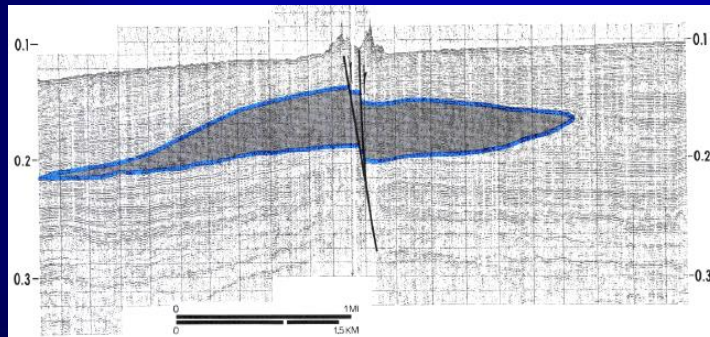
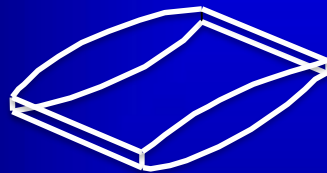
Seismic Stratigraphy

Categories-Seismic Facies Analysis

1- Reflection Configuration

External forms of reflection configuration

Lens



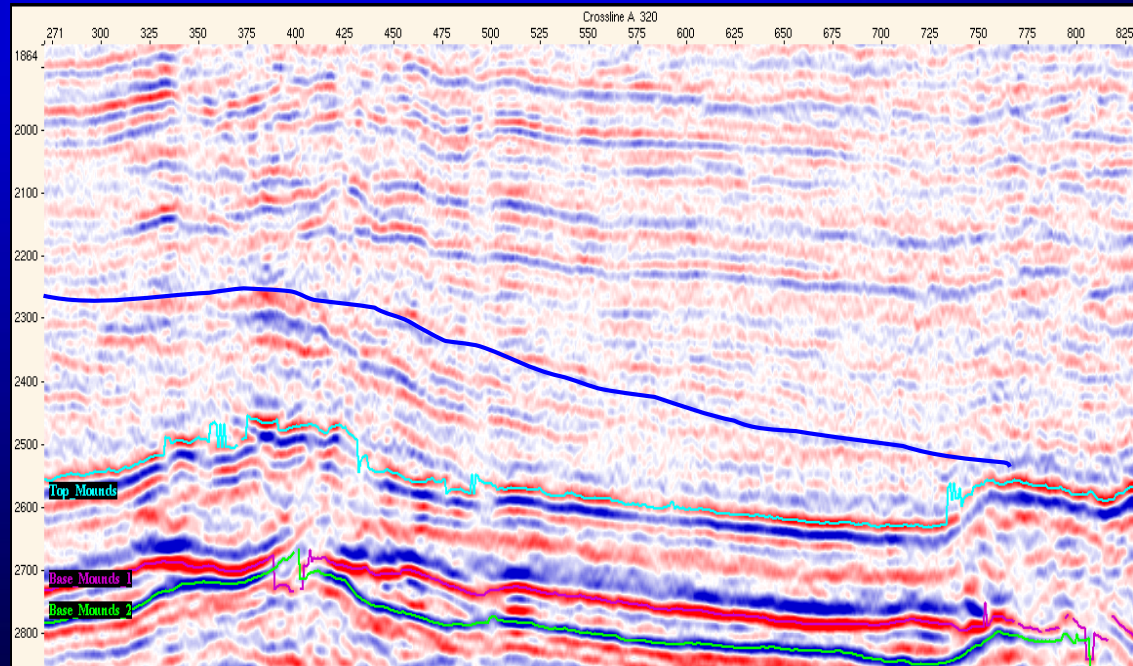
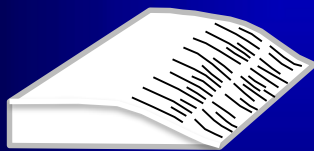
Seismic Stratigraphy

Categories-Seismic Facies Analysis

1- Reflection Configuration

External forms of reflection configuration

Bank



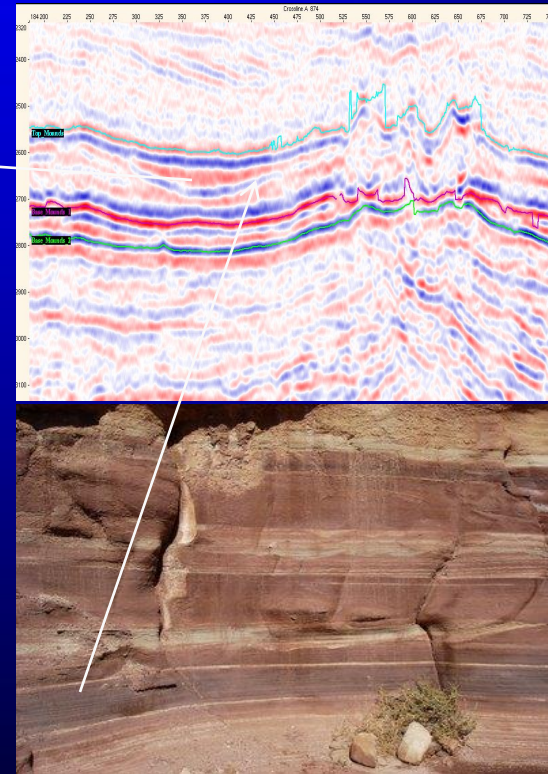
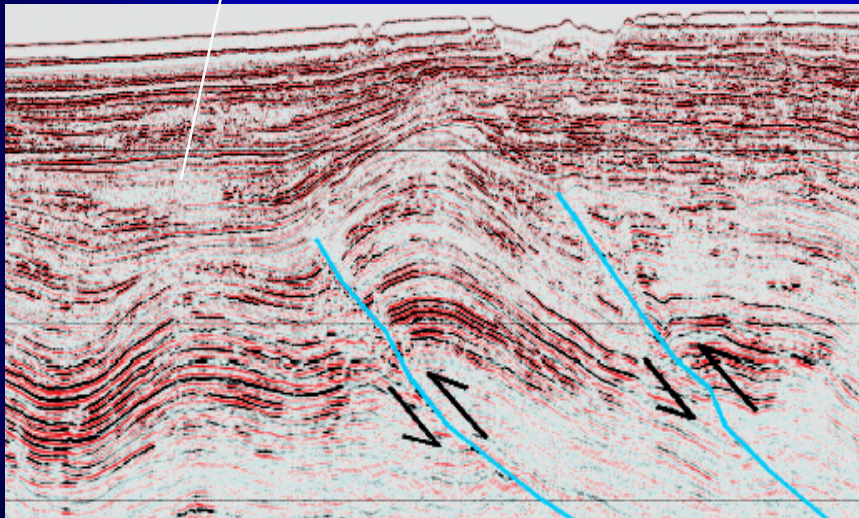
Seismic Stratigraphy

Categories-Seismic Facies Analysis

1- Reflection Configuration

External forms of reflection configuration

Drape

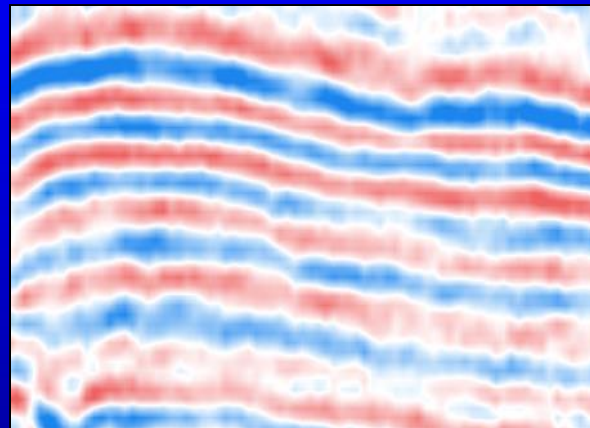
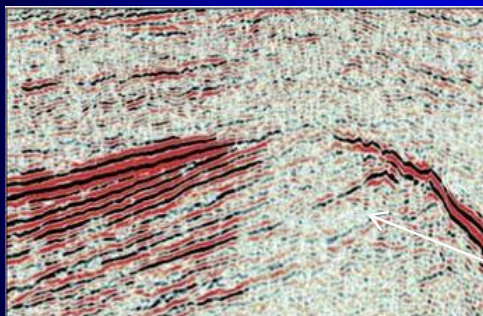


Seismic Stratigraphy

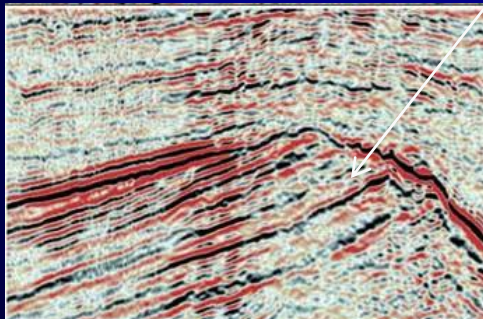
Categories-Seismic Facies Analysis

2- Reflection continuity:

- Bedding continuity
- Depositional processes

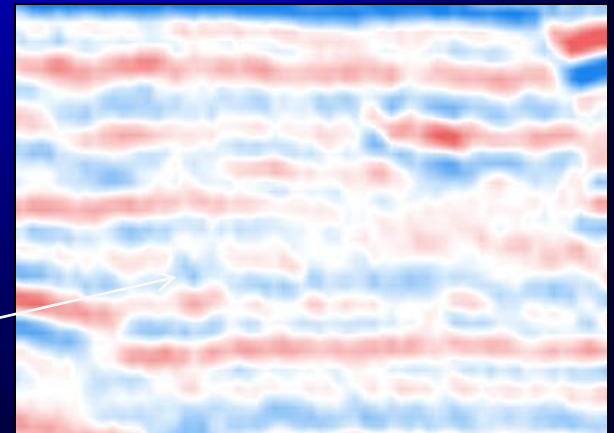


High Continuity
(continuous strata deposited in widespread and uniform environment, (marine conditions))



Difference in continuity due to different shooting parameters

Low Continuity
(sediments deposited with variable energy (by fluvial-Alluvial currents))



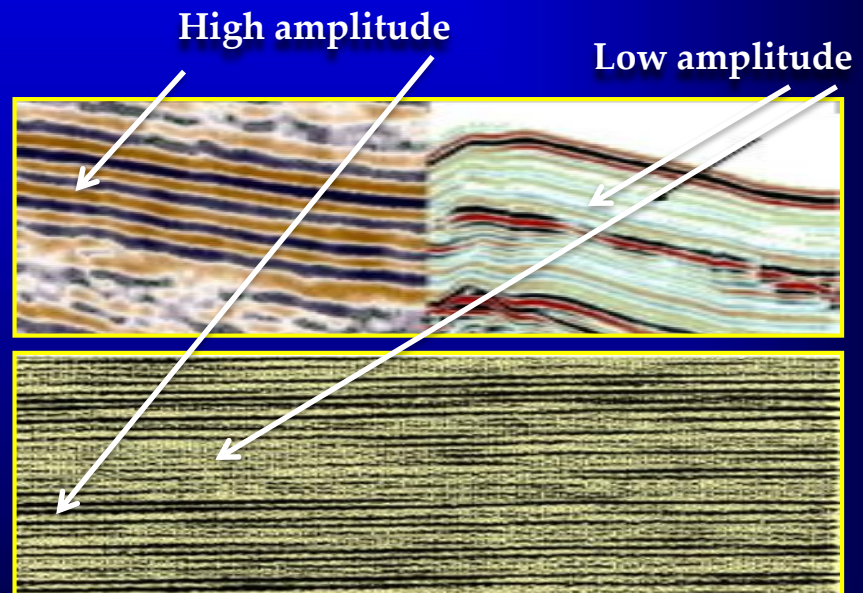
Seismic Stratigraphy

Categories-Seismic Facies Analysis

3- Amplitude

Amplitude is the height of reflection peak and it dependent on the reflection coefficient.

- Vertical change in amplitude can be used to locate **unconformities**.
- Lateral change can be used to help distinguish **seismic facies**.
- Lateral changes in amplitude can help delineate the edges of bright spots



Seismic Stratigraphy

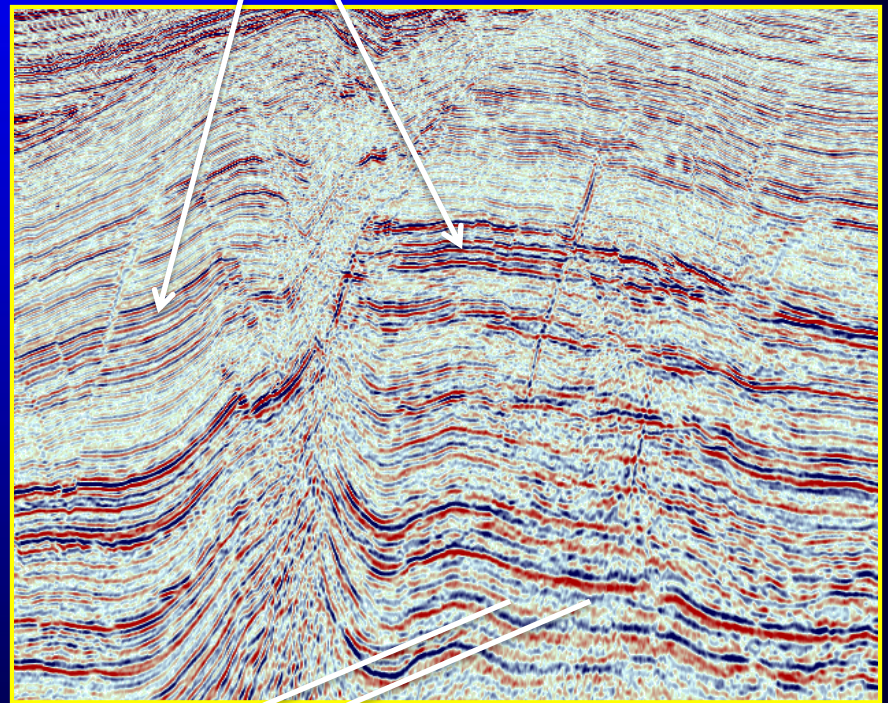
Categories-Seismic Facies Analysis

4- Frequency (Spacing)

It describes the number of reflections per unit time .

- It is a function of both frequency of seismic signal and interference effects.
- Vertical change in spacing can be used to locate boundaries between depositional sequences.
- Lateral change can be used to infer facie

High frequency-small spacing



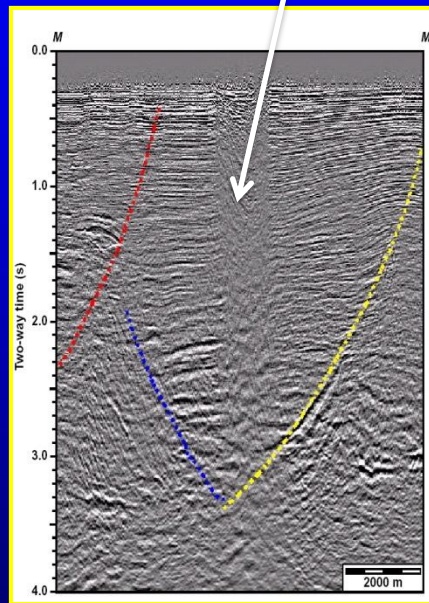
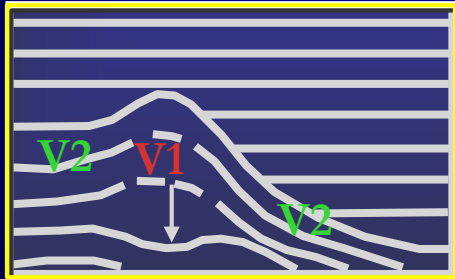
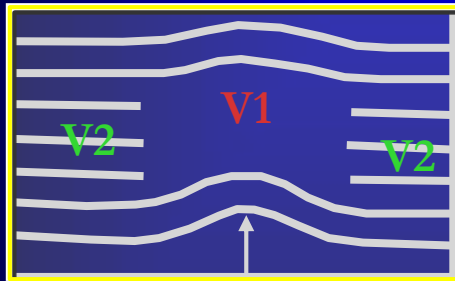
Low frequency-long spacing

Seismic Stratigraphy

Categories-Seismic Facies Analysis

5- Interval velocity:

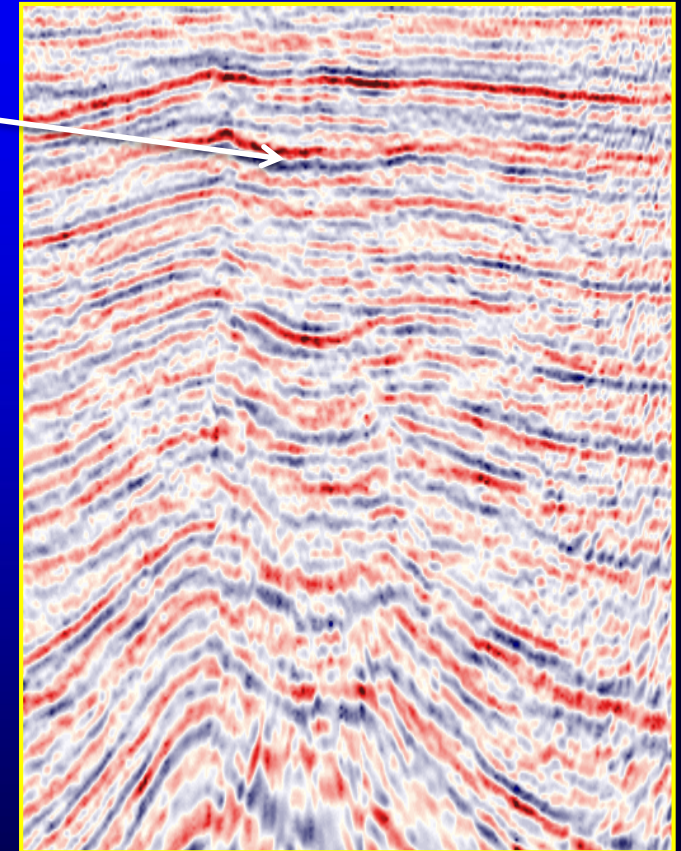
Estimation of lithology
Estimation of porosity
Fluid content



Velocity Anomaly - pull down

$$V1 < V2$$

$$\text{Velocity: } V = (\rho/c)^4$$

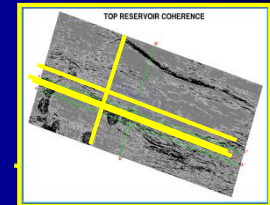
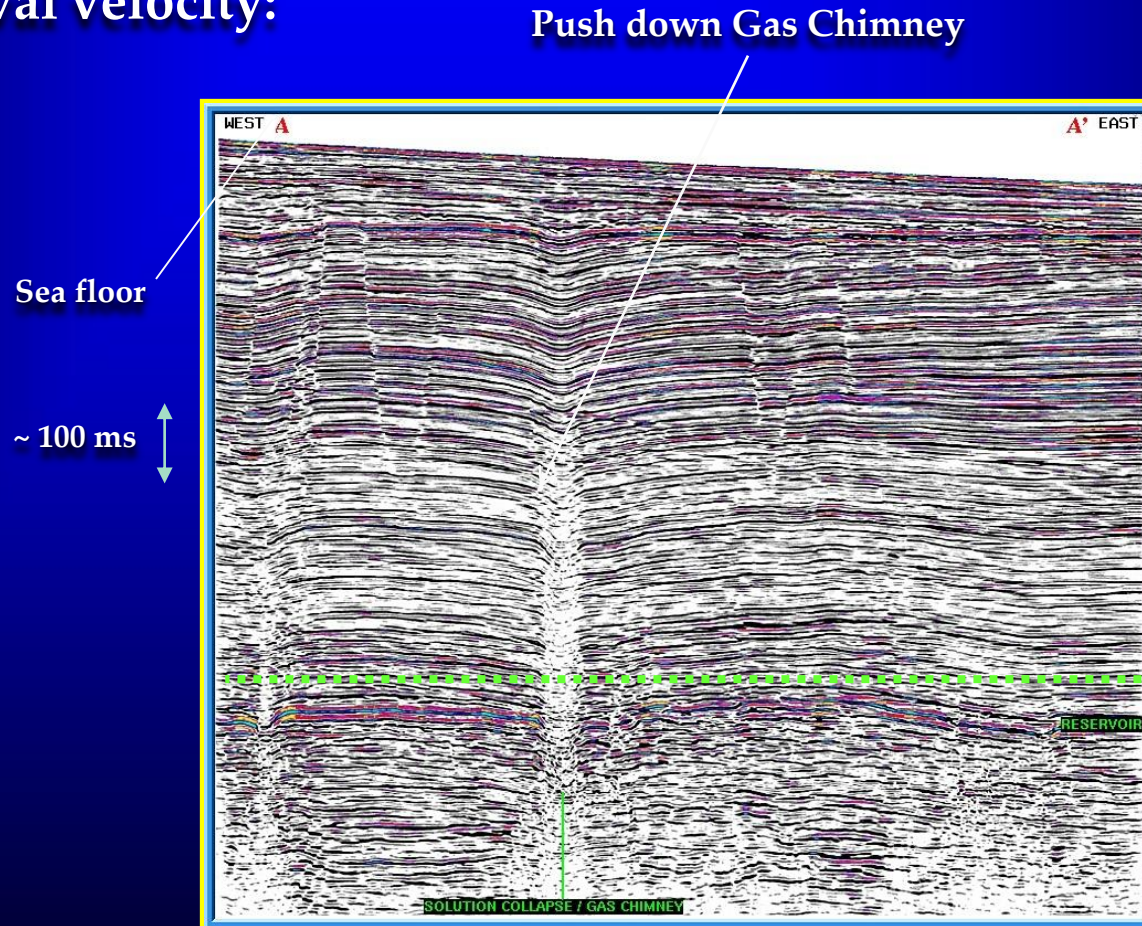


Push down (velocity sag) due to gas accumulation

Seismic Stratigraphy

Categories-Seismic Facies Analysis

5- Interval velocity:



Plio-
Pleistocene
turbidities

Top Reservoir
(= Top A)

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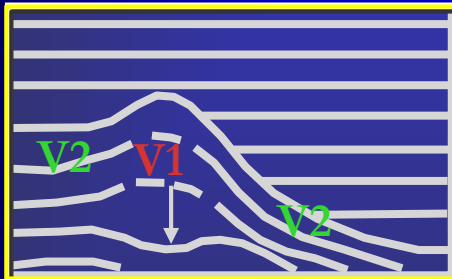
Gas chimney emanating from sinkhole;
amplitude reduction and structural / gas s

Seismic Stratigraphy

Categories-Seismic Facies Analysis

5-Interval velocity:

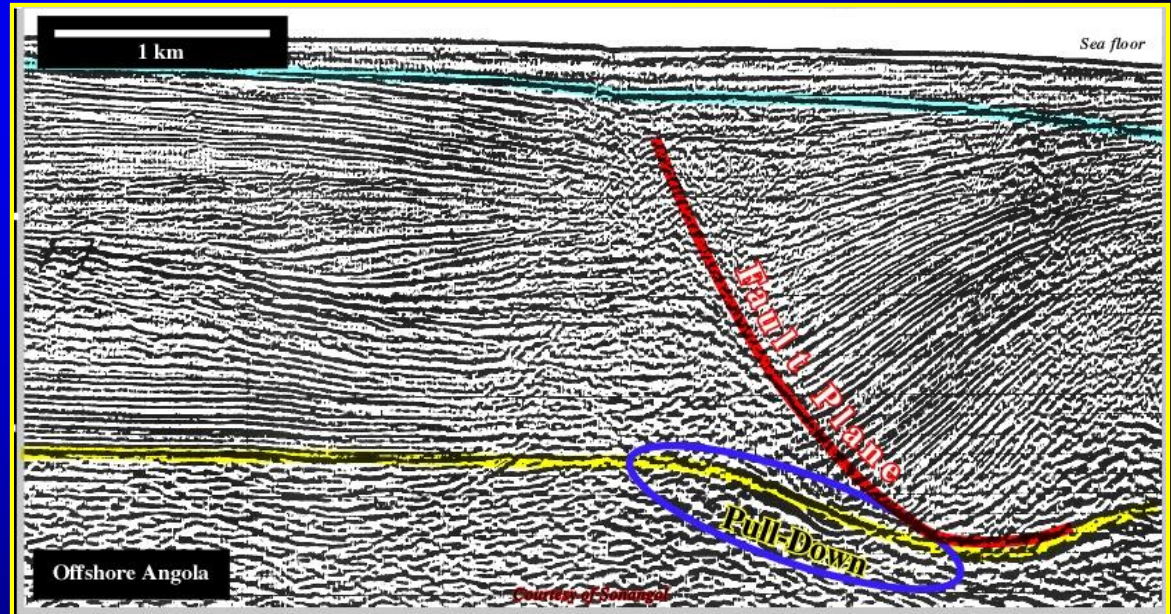
Estimation of lithology
Estimation of porosity
Fluid content
Pull up & Pull down



Velocity Anomaly - pull down

$$V1 < V2$$

$$\text{Velocity: } V = (\rho/c)^4$$

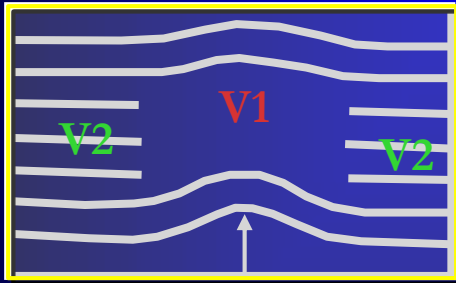


On this seismic line from offshore Angola, the pull-down of the yellow marker (bottom of the evaporitic interval) is induced by the lateral change of the interval-velocity created by the normal fault which limits a Upper Tertiary depocenter. Indeed, such a fault put limestones (upthrown block) and shales (downthrown block in juxtaposition).

Seismic Stratigraphy

Categories-Seismic Facies Analysis

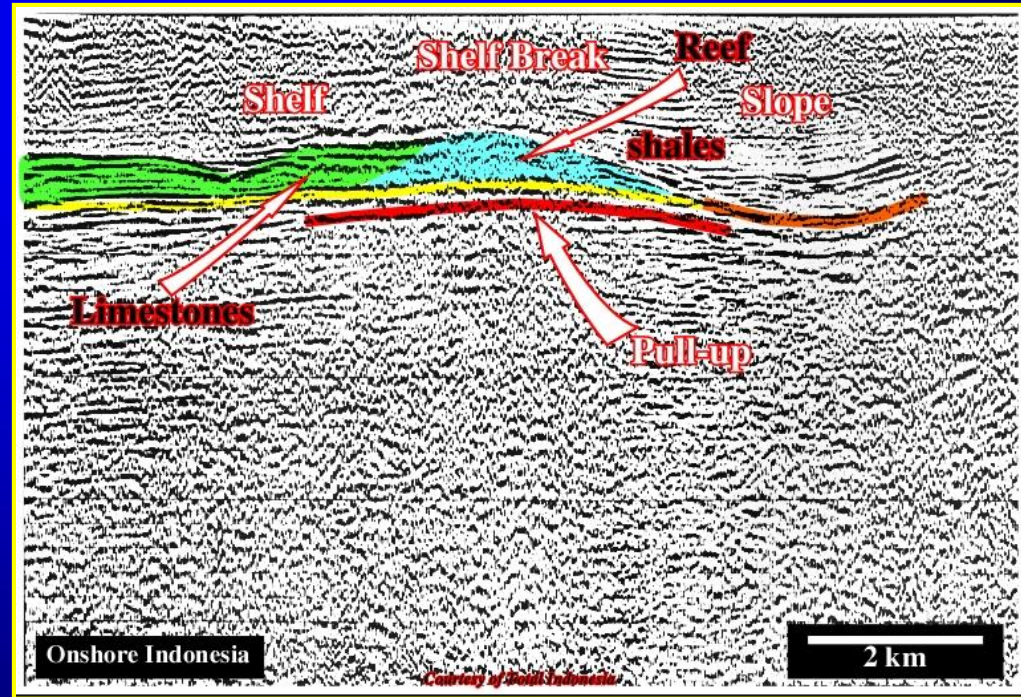
5- Interval velocity:



Velocity Anomaly - pull up

$$V1 < V2$$

$$\text{Velocity: } V = (\rho/c)^4$$

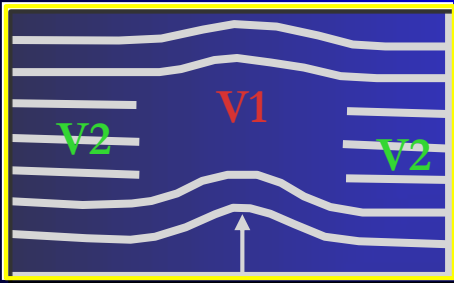


On this reef geological model, above a planar limestone sole (light blue), a reef with a compression wave velocity of 5490 m/s, is laterally bounded by shaly sediments (yellow) with a much lower velocity (3660 m/s), which are overlain by even slower sediments (brown interval, 3050 m/s). The seismic answer of such a model is roughly depicted on the right. The horizon associated with the bottom of the reef shows a significant pull-up.

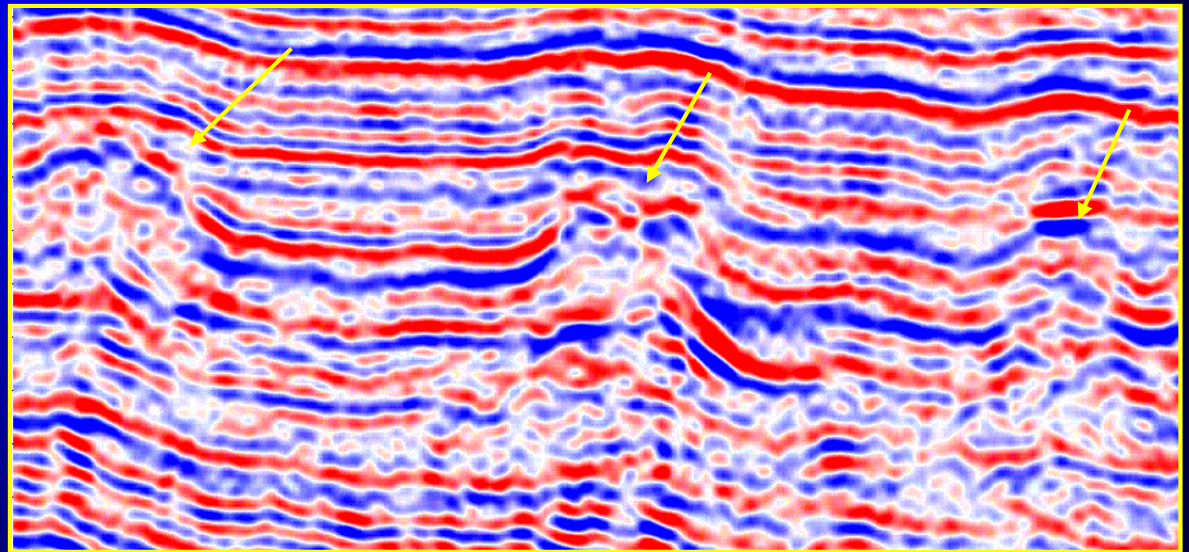
Seismic Stratigraphy

Categories-Seismic Facies Analysis

5- Interval velocity:



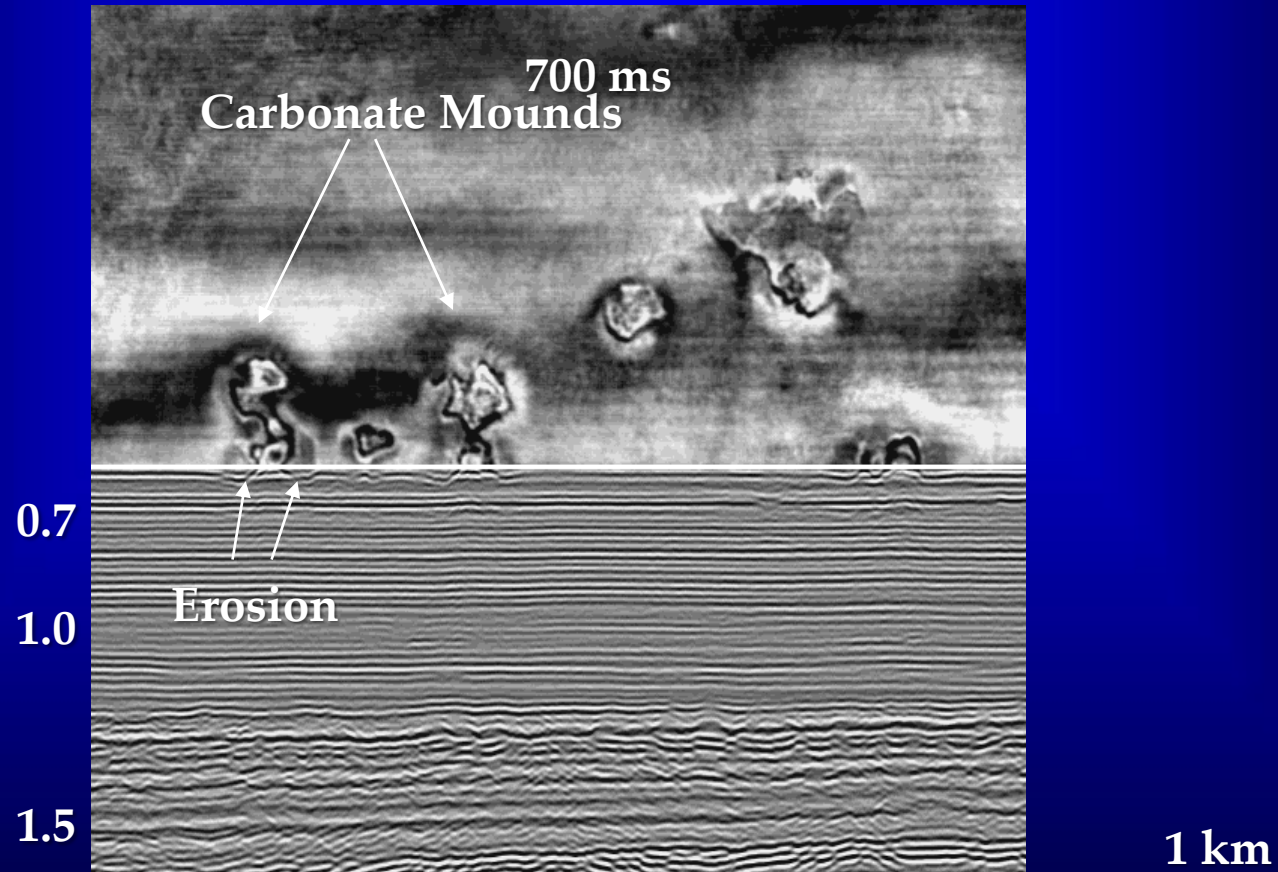
Velocity Anomaly - pull up



Palaeozoic carbonate reef build-ups (Barents Sea)

Seismic Stratigraphy

Categories-Seismic Facies Analysis



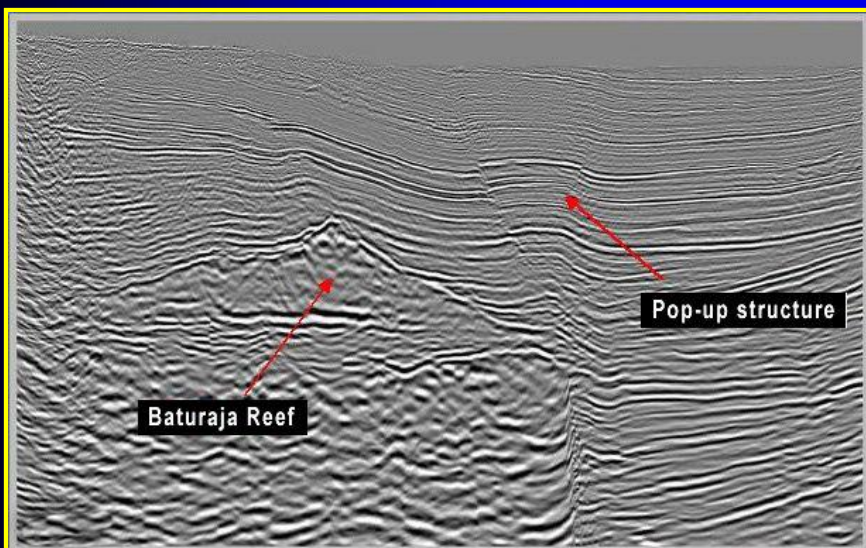
3D Seismic, Composite Display, Danish North Sea

Seismic Stratigraphy

Categories-Seismic Facies Analysis

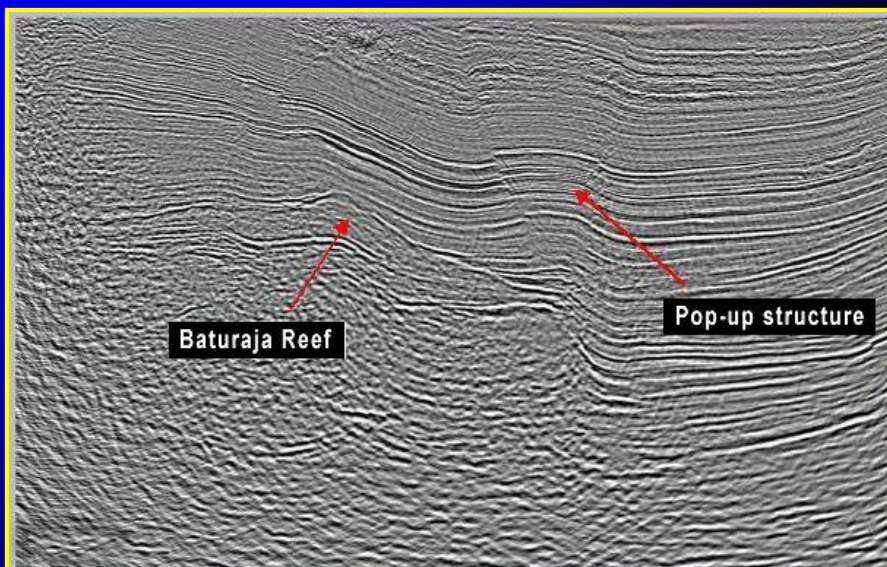
5- Interval velocity:

PSDM Migration No pull up



Prestack depth migration reveals a reef structure with significant closure, well-defined crest and flanks, and onlapping reflectors

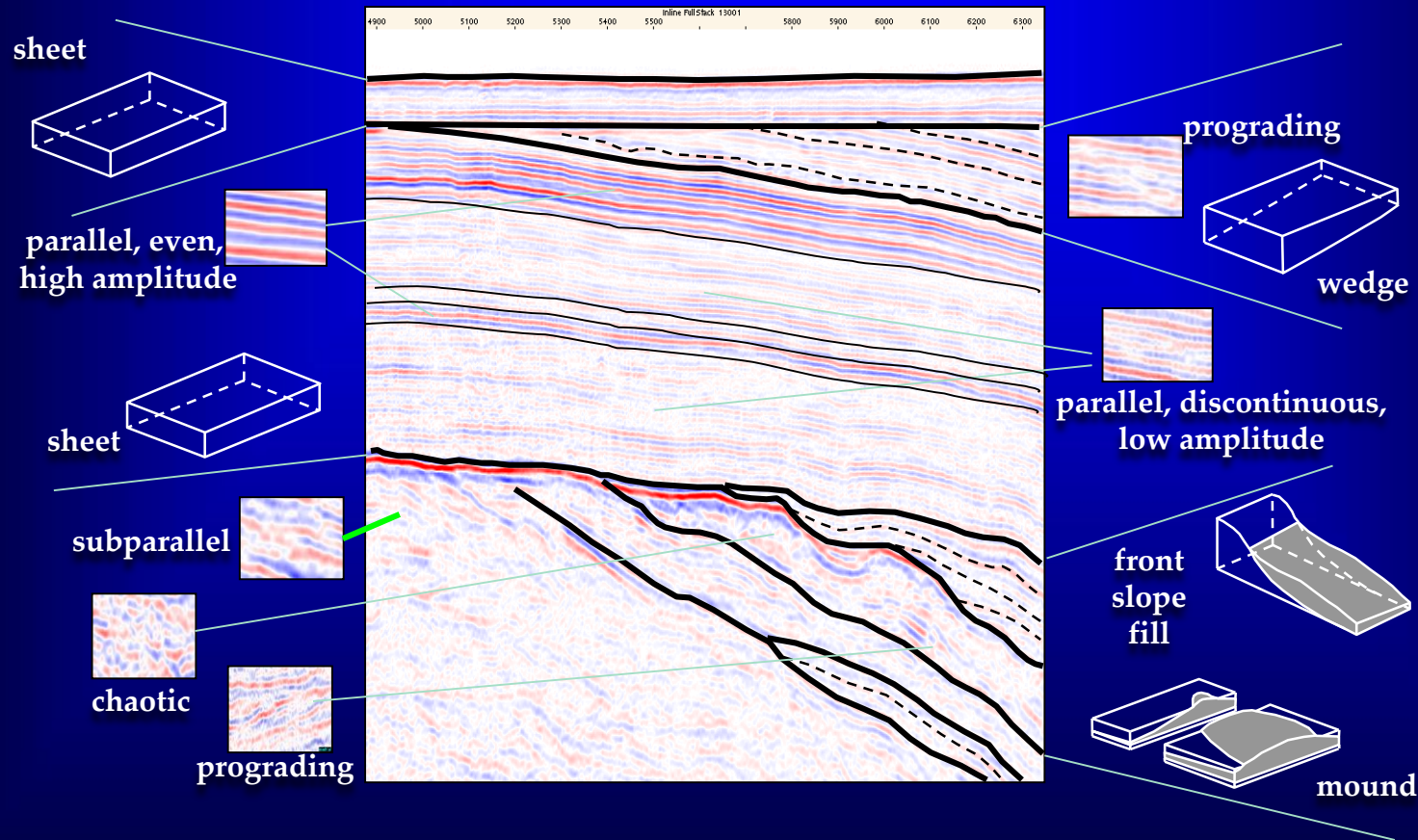
Time Migration- pull up anomaly from reef



Time migration indicates a reef buildup, with low relief and an indistinct crest

Seismic Stratigraphy

Categories-Seismic Facies Analysis



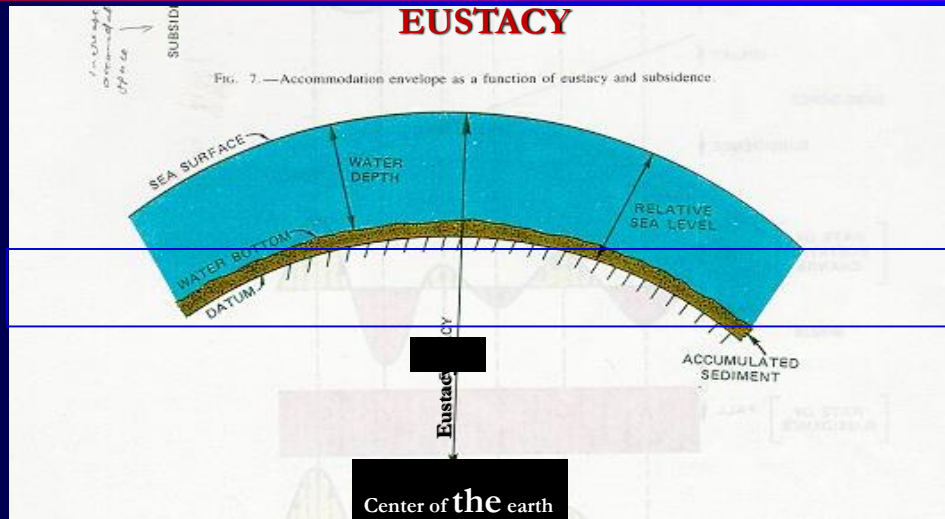
6. Sequence Stratigraphy

Fundamental Sequence Stratigraphic Concepts

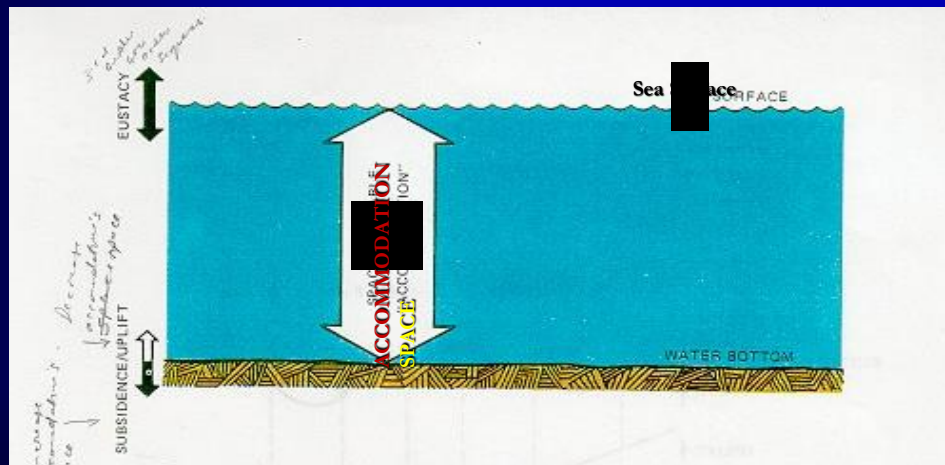
Orders of Stratigraphic Cyclicity

ORDER	DURATION (M.Y.)		STRATIGRAPHIC NOMENCLATURE		SCALE	Seismic
	RANGE	MODE				
1st	350 - 500	450	Megasequence Set		Major Systems and Basins <i>> 1000's of meters</i>	
	50 - 100 +	80	Megasequence			
2nd	20 - 50 +	30	Supersequence Set		Systems and Series <i>100's 10 1000's of meters</i>	
	5 - 20 +	10	Supersequence			
3rd	0.5 - 5	1	GREENHOUSE Sequence	ICEHOUSE Composite Sequence	Fields <i>10's to 100's of meters</i>	
4th	0.05 - 0.5	0.1; 0.45	Parasequence Set Parasequence	High Frequency Sequence	Fields and Reservoirs <i>1 - 10's of meters</i>	
5th	0.01 - 0.05	0.02; 0.04	Parasequence Bed Sets	Parasequence Set Parasequence	Reservoirs <i>< 1m to a few meters</i>	
> 6th	< 0.01		Beds Laminae	Bed Sets Beds Laminae	<i>< 1m</i>	Outcrops and Cores

Sea Level Fluctuations



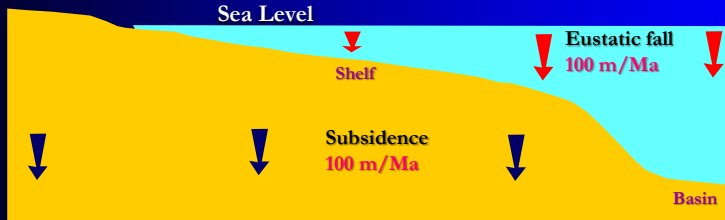
Eustacy = Global sea level measured from center of earth



Relative Sea Level:-
Position of the sea surface relative to a datum (I.e basement/sea bed) and hence incorporates local subsidence/uplift

Sea Level Fluctuations

Rate of Eustatic fall = Rate of Subsidence



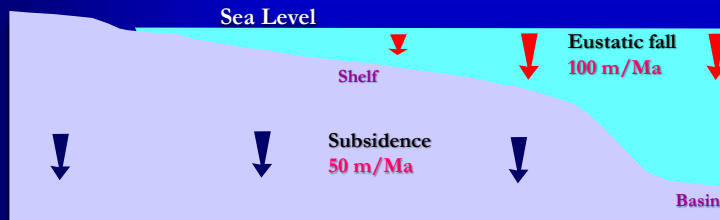
Basin A

Sea Level Drop = 100 m

Subsidence = 100 m

No change in relative sea level

Rate of Eustatic fall > Rate of Subsidence



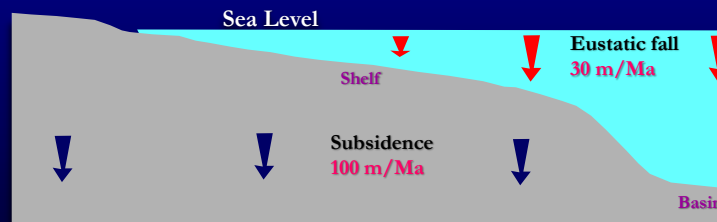
Basin B

Sea Level Drop = 100 m

Subsidence = 50 m

Relative sea level dropped by 50 m

Rate of Eustatic fall < Rate of Subsidence



Basin C

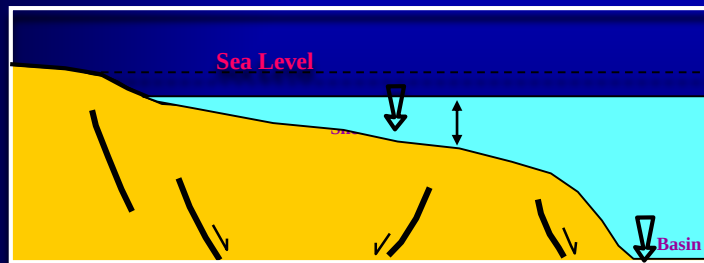
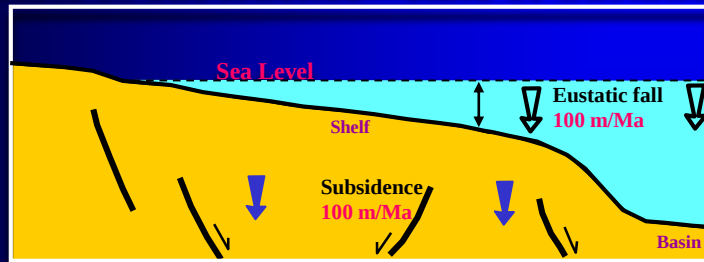
Sea Level Drop = 30 m

Subsidence = 100 m

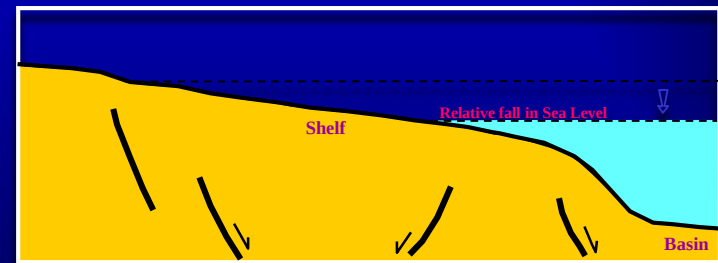
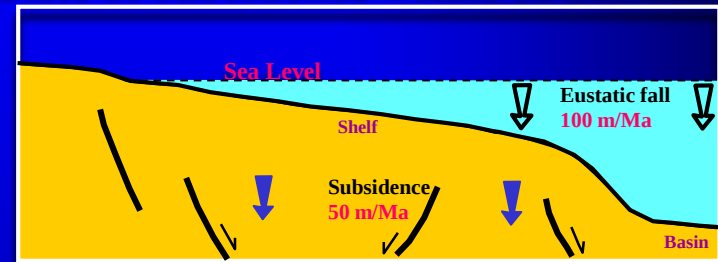
Relative sea level
raised by 70 m

Rate of Subsidence vs Rate of Eustatic fall

Type-2 Seq. Boundary Type-1 Seq. Boundary
 Rate of subsidence = Rate of Eustatic fall Rate of subsidence < Rate of Eustatic fall



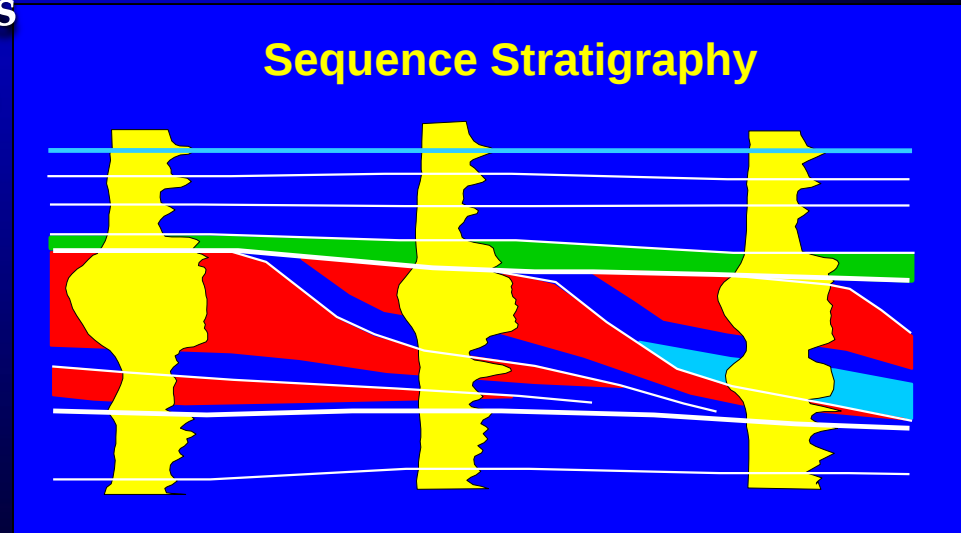
- No relative fall in sea level
- LST represented by SMST



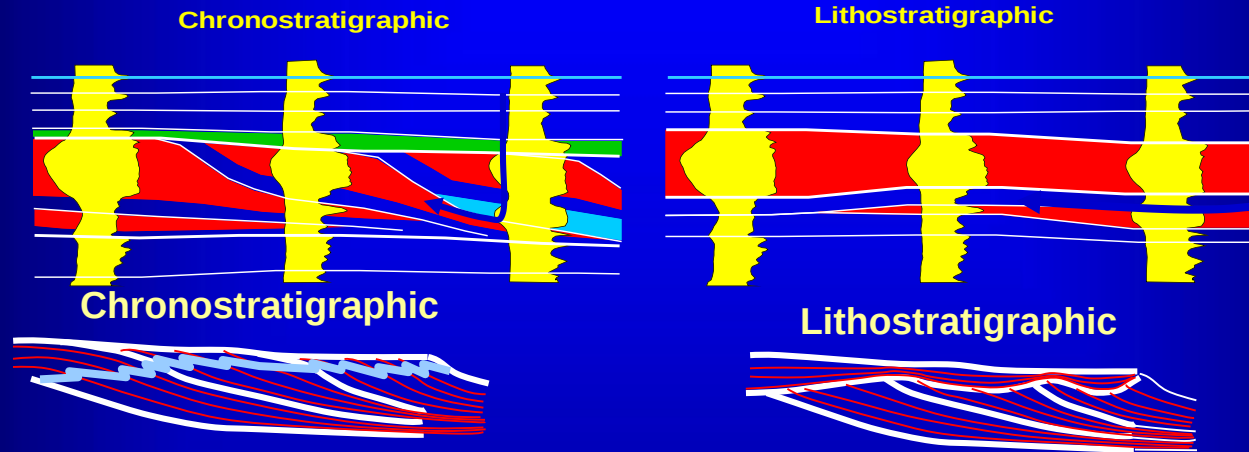
- Relative fall in sea level
- Shelf exposed
- Erosion on the shelf/incised valley
- Slope fan/BFF deposited in the basin

What is Sequence Stratigraphy?

- Subdivision of Rock Record Using a Succession of Depositional Sequences Composed of Genetically Related Strata That Can Be Used for Local to Regional Correlation
- Identification Based On:
 - Nature of bounding surfaces
 - Internal geometric relations
 - Facies distribution



Chronostratigraphy versus Lithostratigraphy



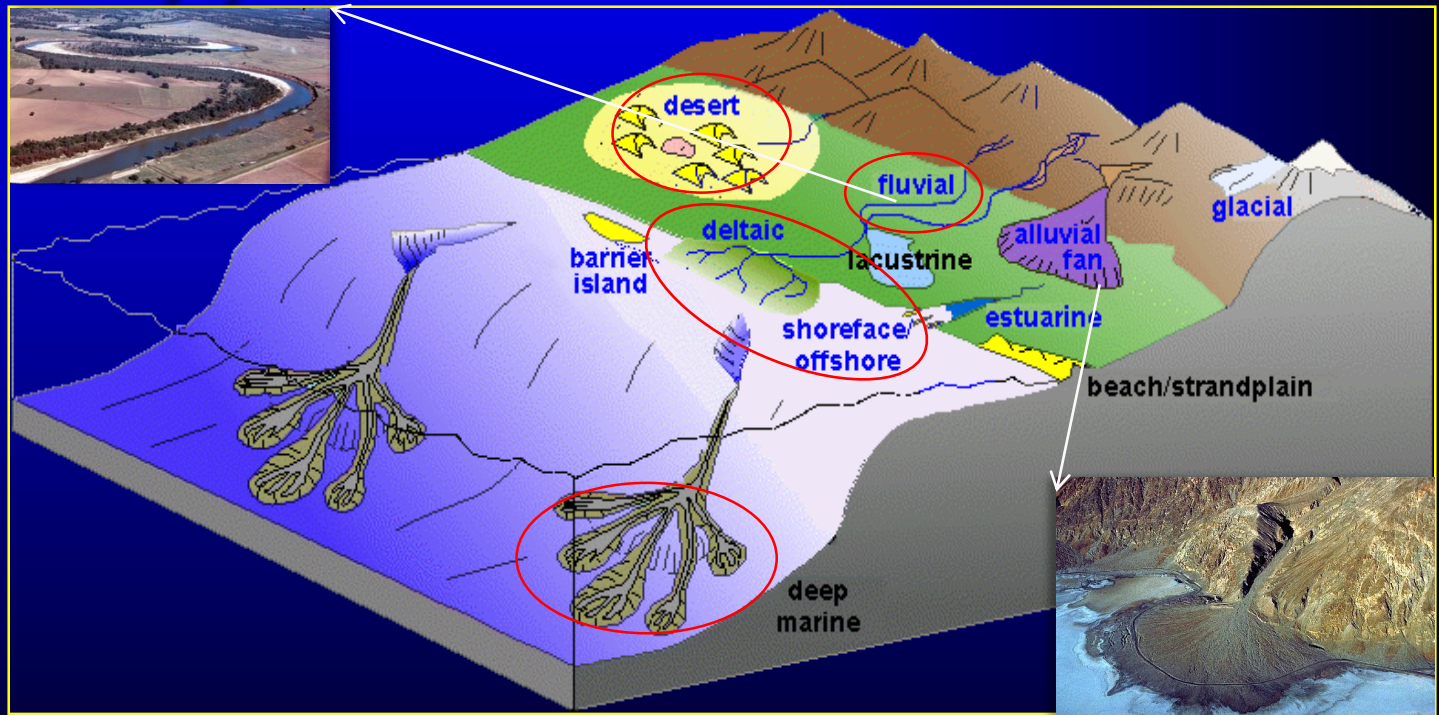
- Provides a Methodology for Placing Strata into a Time-Stratigraphic (Chronostratigraphic) Framework
- Provides Framework for Distribution of Lithofacies as well as Depositional and Diagenetic Processes
- Provides Improved Predictions of Play Element Distribution, By-Passed Pay Zones, Step-Out Potential

Seismic Sequence Stratigraphy

Principle 1

Sedimentation

Major sedimentary systems.



Seismic Sequence Stratigraphy

Principle 1

Sedimentation

Sedimentary Facies

Two types of facies

1) **Lithofacies:**

Distinguishing characteristics are lithologic.

2) **Biofacies:**

Can have different adjacent biofacies in the same lithology.

Can be very sensitive to small environment differences.

Seismic Sequence Stratigraphy

Principle 1 Sedimentation

Flow and Sediment Motion

- Fluid and sediment gravity flows tend to move from high to low elevations, following pathways that require the least amount of energy for fluid and sediment motion.
- Flow velocity is directly proportional to slope magnitude.
- Flow discharge (subaerial or subaqueous) is equal to flow velocity times cross-sectional area.
- Sediment load (volume) is directly proportional to the transport capacity of the flow, which reflects the combination of flow discharge and velocity.
- The mode of sediment transport (bedload, saltation, suspension) reflects the balance between grain size/weight and flow competence.

Seismic Sequence Stratigraphy

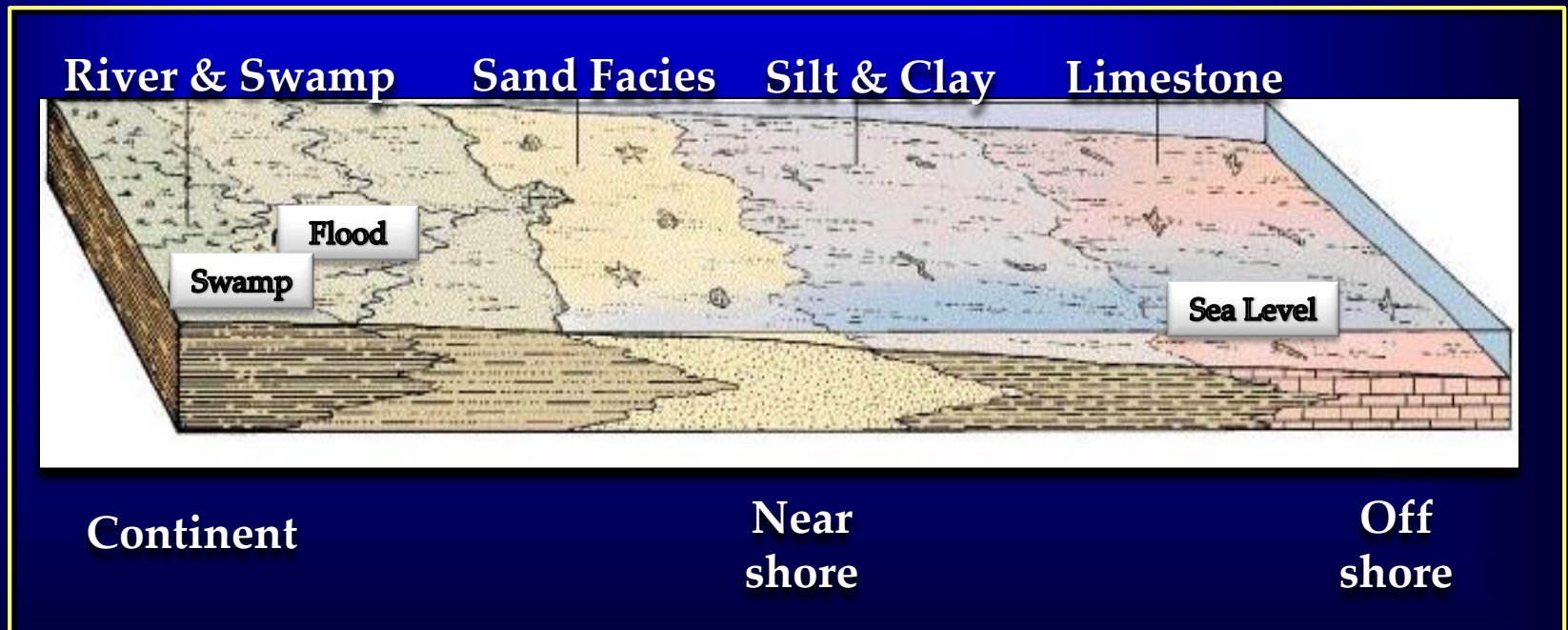
Principle 1

Sedimentation

Idealized Gradation

Near shore = coarse sediment

Off shore = fine sediment Shelf carbonate deposition



Seismic Sequence Stratigraphy

Principle 1

Sedimentation

Transgression and Regression

Transgression:

- Advance of sea over the land

Regression:

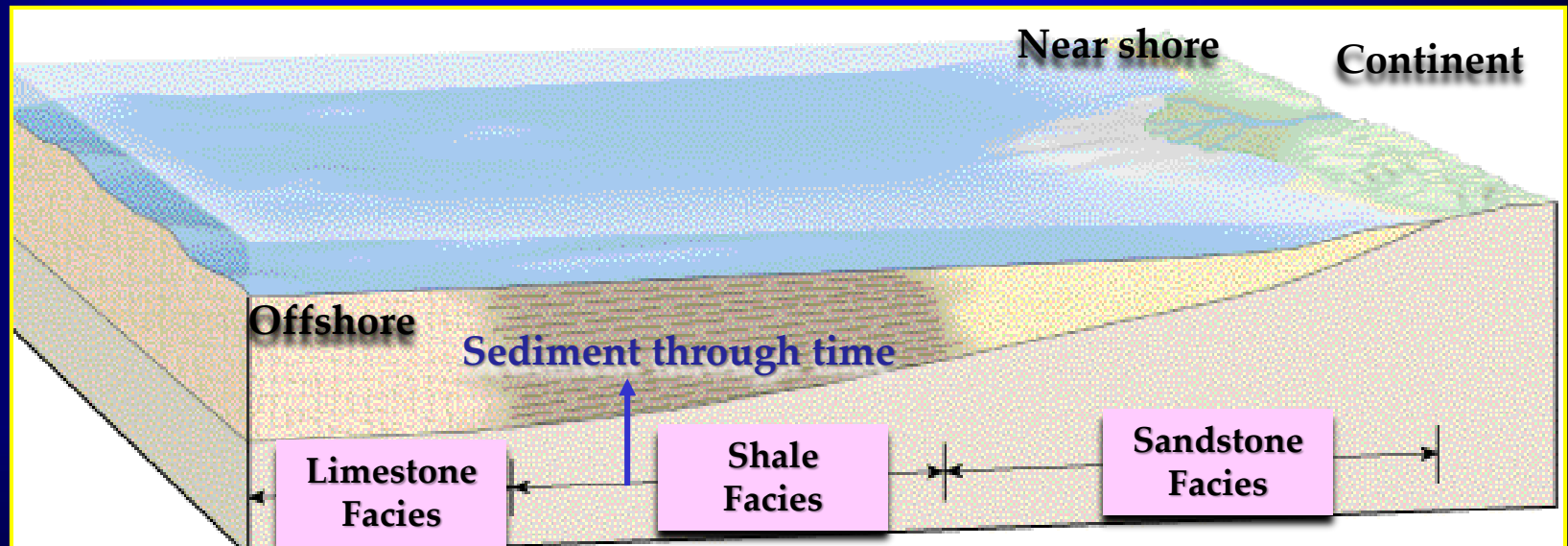
- Retreat of the sea from the land

Seismic Sequence Stratigraphy

Principle 1

Sedimentation

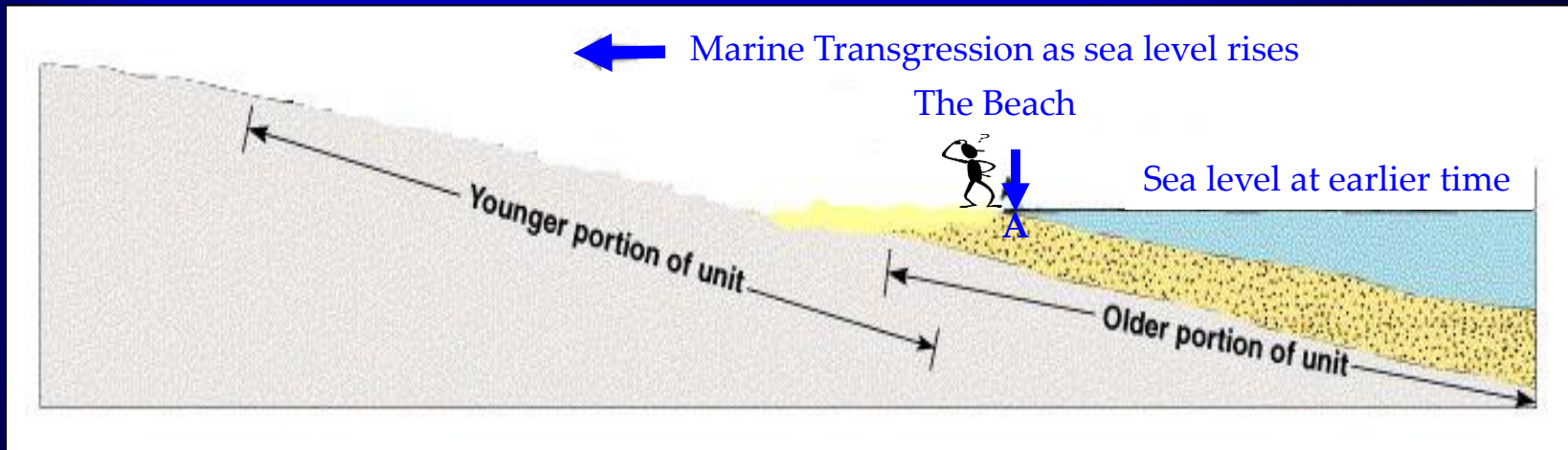
Transgression and Regression
Case of No Sea Level Change



Seismic Sequence Stratigraphy

Principle 1 Sedimentation **Transgression** Sea Level at time A

- Tectonic subsidence (sinking)
- Rise in sea level
- Erosion of shore line

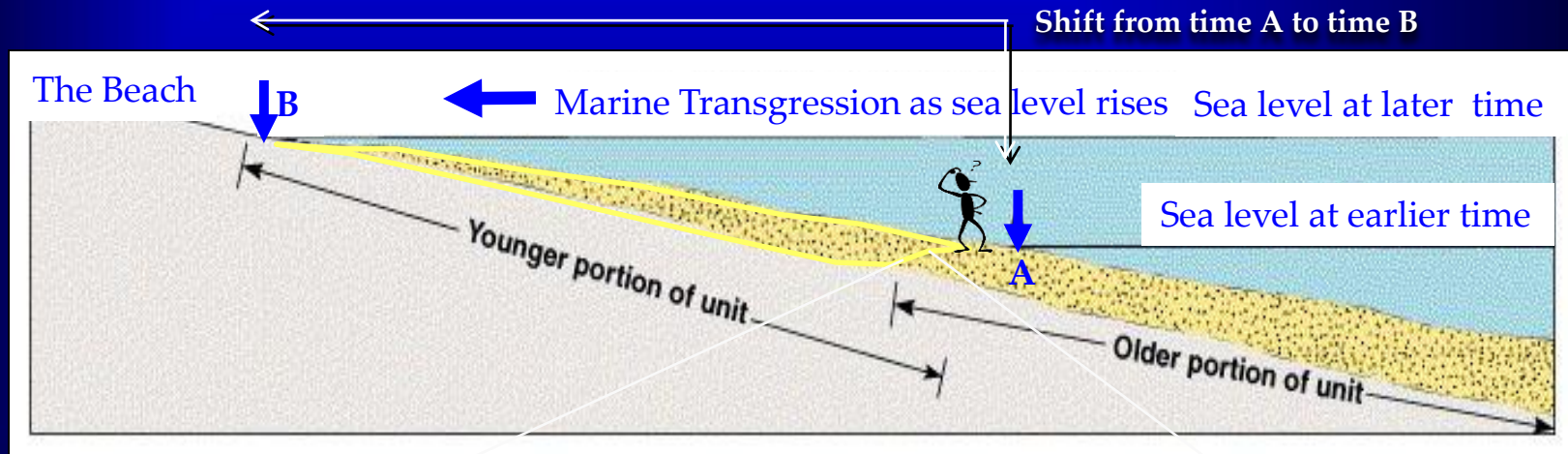


Seismic Sequence Stratigraphy

Principle 1 Sedimentation **Transgression** Sea Level at time B

What causes Transgression

- Tectonic subsidence (sinking)
- Rise in sea level
- Erosion of shore line



Facies shift on-shore resulting rock unit (sandstone) varies in age laterally

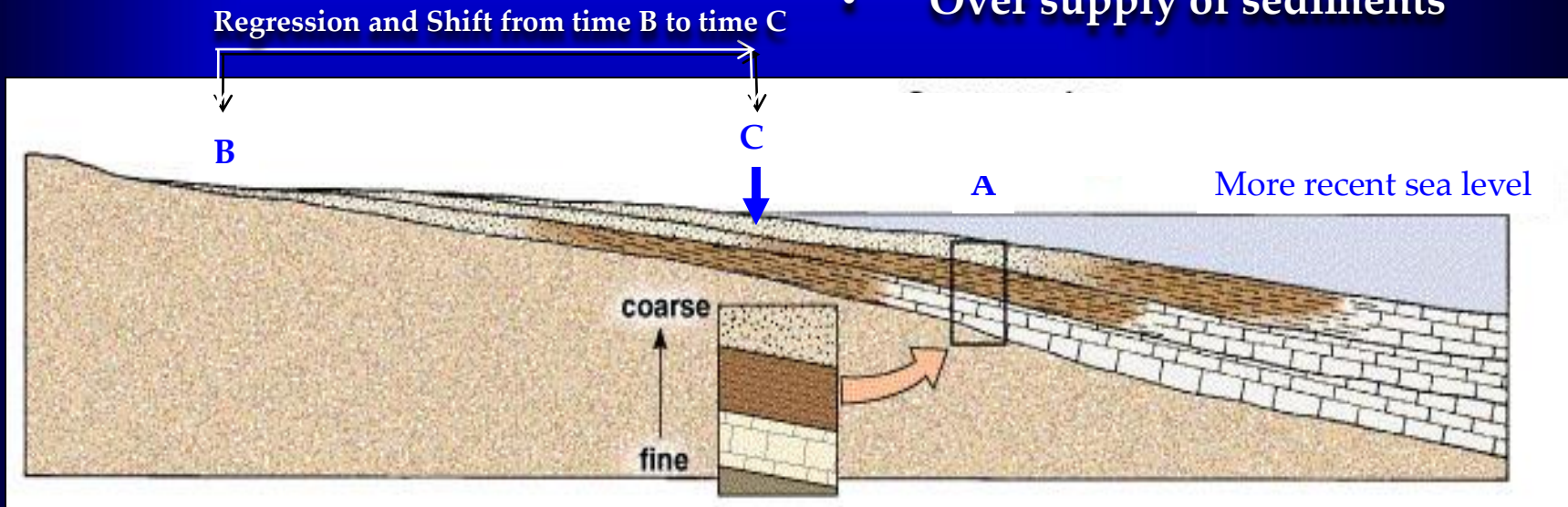
Seismic Sequence Stratigraphy

Principle 1 Sedimentation Regression

Sea Level back to near A

What causes Regression

- Tectonic Uplift
- Drop in sea level
- Over supply of sediments



In one place, facies become more "onshore" (= coarser) up section

Seismic Sequence Stratigraphy

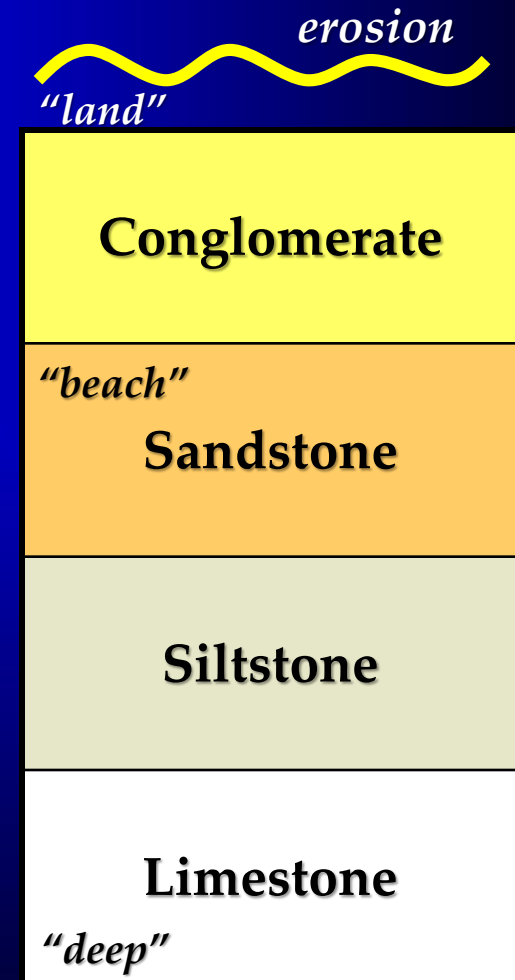
Principle 1 **Sedimentation** **Regression**

- Sediment supply >> Accommodation
- Deep overlain by shallower facies
- Marine overlain by non-marine facies
- Offshore overlain by nearshore fossils
- Coarsening-upward sequence
- Forward-stepping parasequences
- Relative fall in base level

Seismic Sequence Stratigraphy

Principle 1 Sedimentation Regression

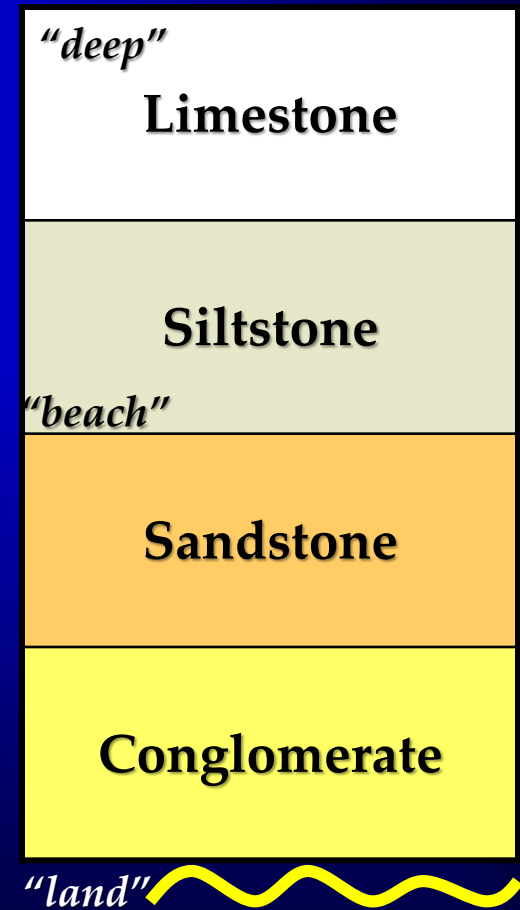
- In a vertical column, facies become progressively more "on shore" (*coarser*) up section.



Seismic Sequence Stratigraphy

Principle 1 Sedimentation Transgression

- In a vertical column, facies become progressively more "off shore" (finer) up section.



Seismic Sequence Stratigraphy

Principle 1

Sedimentation

Sea Level Changes

- When constant sea level is maintained the shoreline and delta prograde outward (shoreline regresses).
- If sea level rises at a constant rate, the shoreline first progrades outward, but the progradation rate is suppressed.
- If sea level continues to rise, progradation is eventually reversed and the shoreline is pushed landward.
- If sea level still continues to rise, sediment transport at the shoreline drops to zero, the delta is drowned and the shoreline rapidly moves landward (transgresses).

Whether or not a delta continues to prograde, or instead is drowned depends on a) the rate and duration of sea level rise (higher values favor drowning) and sediment supply at the bedrock-alluvial transition (a higher value favors continued progradation).

Seismic Sequence Stratigraphy

Principle 1 Sedimentation

Walther's Law

- A vertical sequence represents facies that were once laterally continuous.
- The relative sequence is more important than absolute completeness.

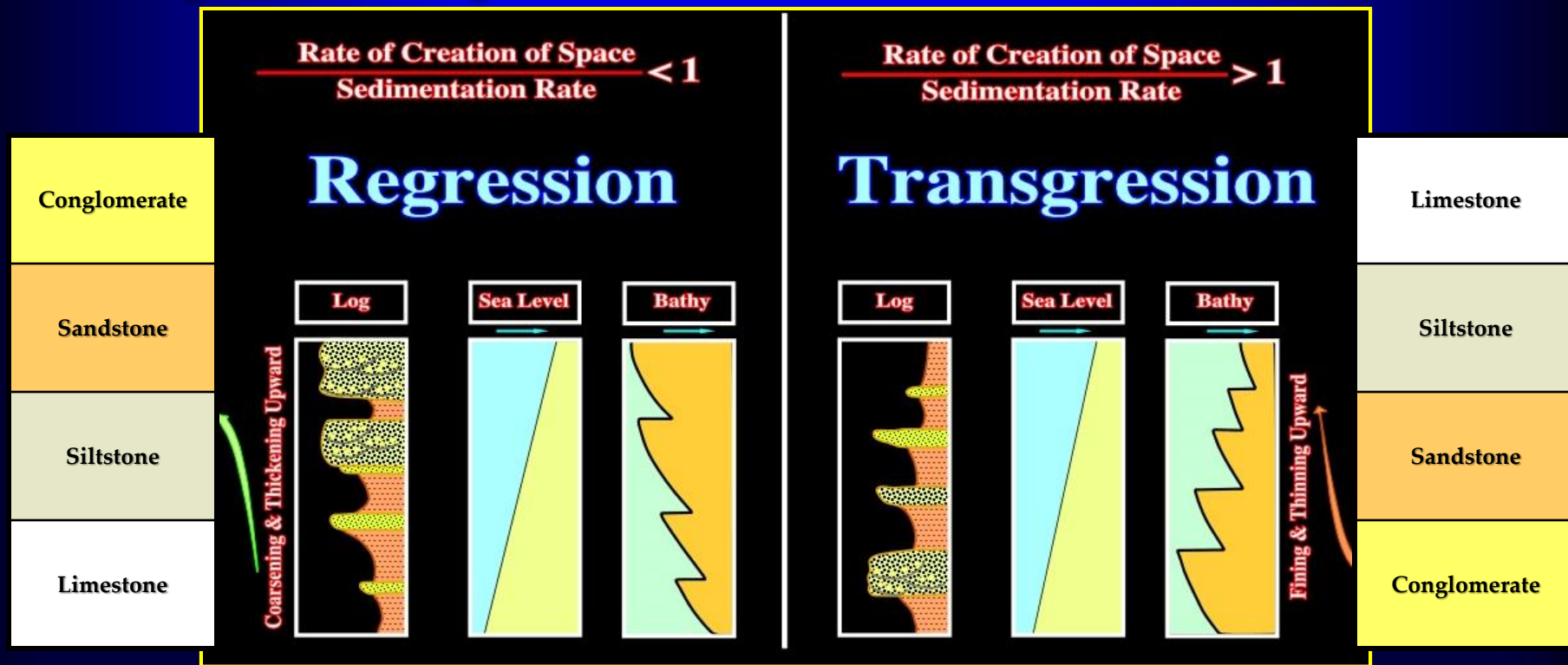
Sandstone
Shale
Limestone



Seismic Sequence Stratigraphy

Principle 1 Sedimentation

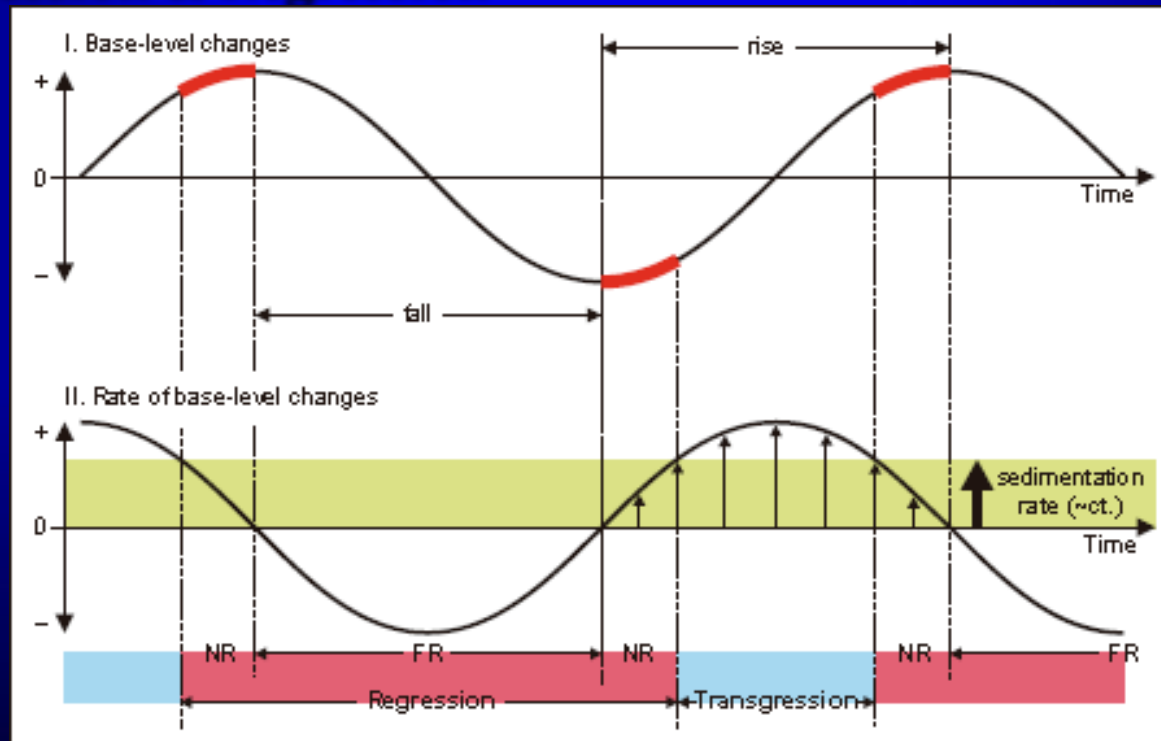
Transgression and Regression



Seismic Sequence Stratigraphy

Principle1 Sedimentation

Transgression & Regression

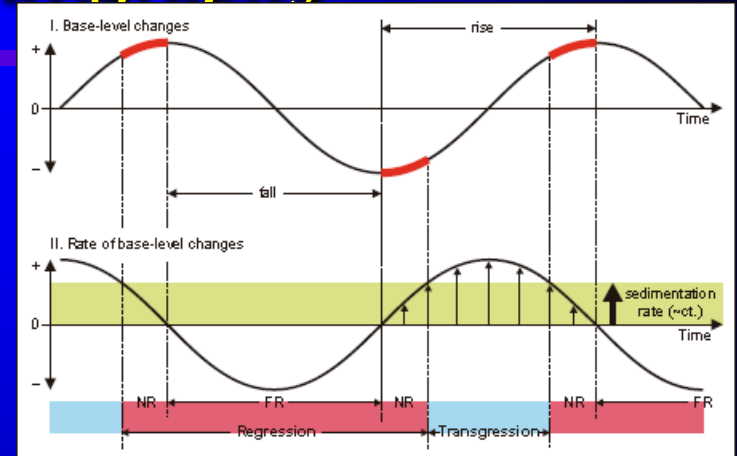


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Seismic Sequence Stratigraphy

Principle 1 Sedimentation

Transgression & Regression



Concepts of transgression, normal regression, and forced regression, as defined by the interplay between base-level changes and sedimentation. The top sine curve shows the magnitude of base-level changes through time. The thicker portions on this curve indicate early and late stages of base-level rise, when the rates of base-level rise (increasing from zero and decreasing to zero, respectively) are outpaced by sedimentation rates. The sine curve below shows the rates of base-level changes. Note that the rates of base-level change are zero at the end of base-level rise and base-level fall stages (the change from rise to fall and from fall to rise requires the motion to cease). The rates of base-level change are the highest at the inflection points on the top curve. Transgressions occur when the rates of base-level rise outpace the sedimentation rates. For simplicity, the sedimentation rates are kept constant during the cycle of base-level shifts. The reference base-level curve is shown as a symmetrical sine curve for simplicity, but no inference is made that this should be the case in the geological record. In fact, asymmetrical shapes are more likely, as a function of particular circumstances in each case study (e.g., glacio-eustatic cycles are strongly asymmetrical, as ice melts quicker than it builds up), but this does not change the fundamental principles illustrated in this diagram. Abbreviations: FR—forced regression; NR—normal regression.

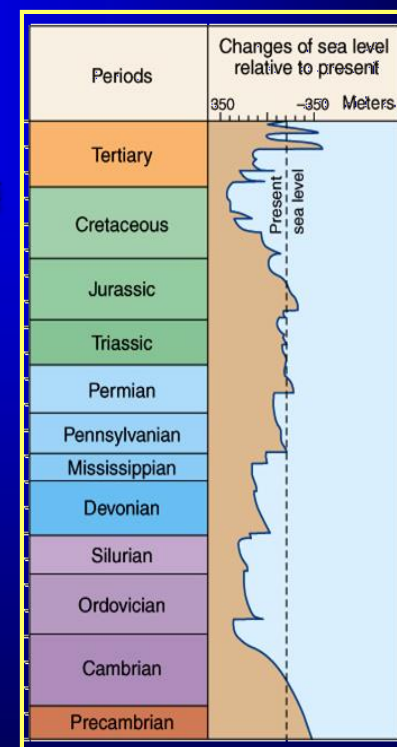
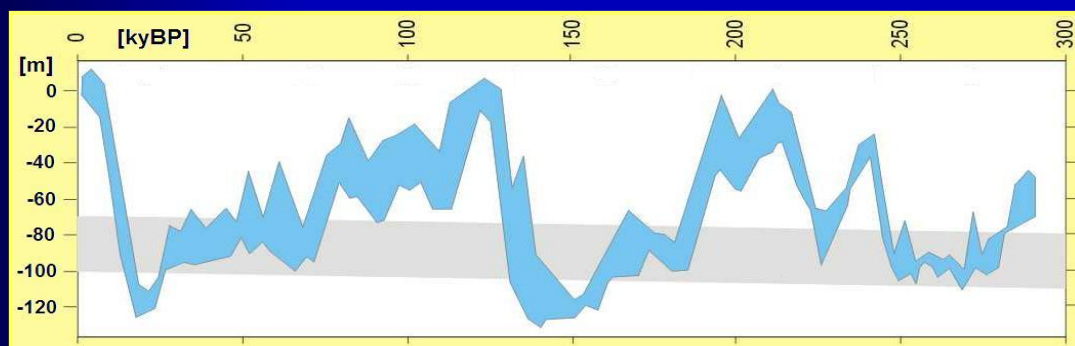
Seismic Sequence Stratigraphy

Principle 2

Eustatic Sea Level changes

Sea-level changes control the succession of sediments that we see in a sedimentary basin

Sea-level have risen and fallen many times in the past



Transgression

Sea-level rises and coastline migrates inland

Regression

Sea-level falls and coastline migrates seaward

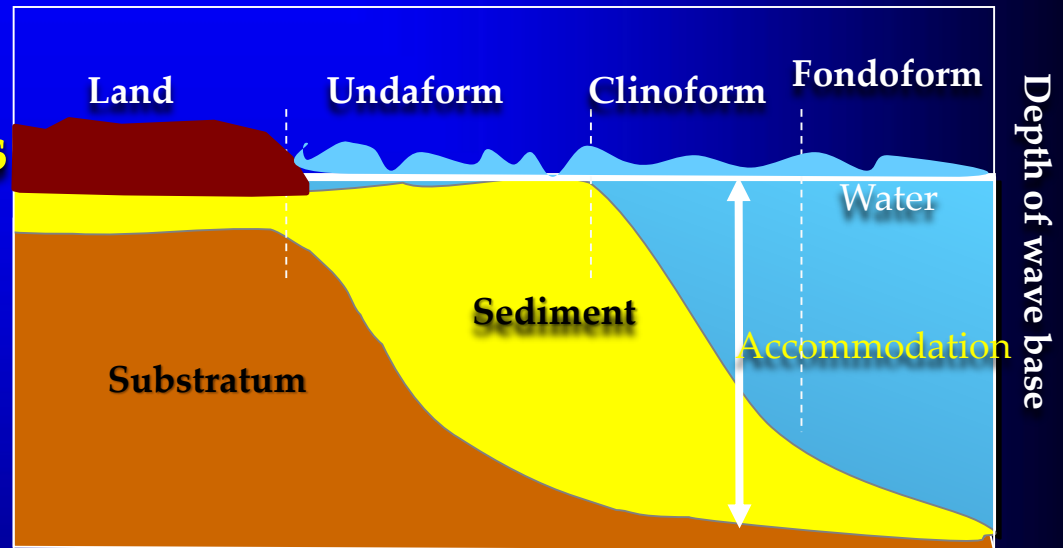
Seismic Sequence Stratigraphy

Principle 2

Eustatic Sea Level changes

- Sediments accumulate in sedimentary basins
- Accommodation: available space where sediments can be accumulated at certain time period.
- On land, base level is set by the equilibrium profile of river systems.
- In marginal marine settings, base level is often the same as sea level.
- In the deep sea there is no base level and sedimentation is controlled only by sediment supply.

Changes in base level allow the sedimentary record to preserve evidence of geological events:

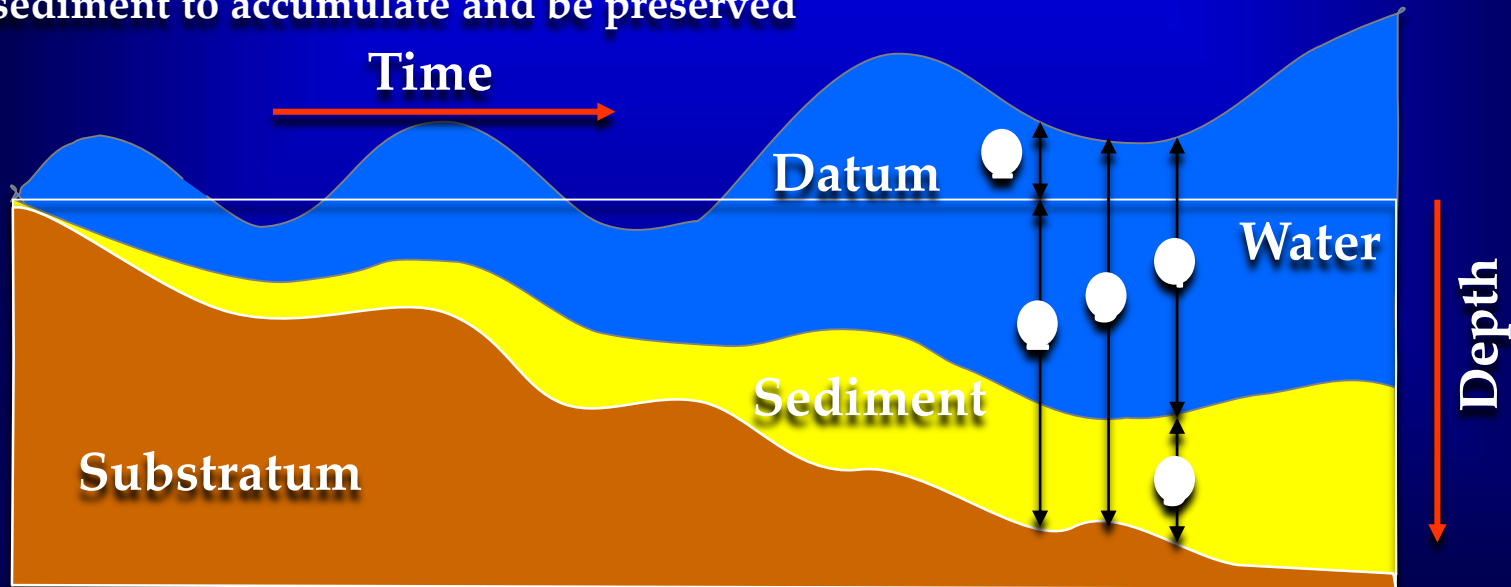


Seismic Sequence Stratigraphy

Principle 2

Eustatic Sea Level changes

Subsidence: Progressive depression of the basin (Earth's crust) which allow sediment to accumulate and be preserved



1: Eustatic level 2: Subsidence 3: Accommodation 4: Depth 5: Effective Accommodation

Seismic Sequence Stratigraphy

Principle 2

Eustatic Sea Level Changes (Global Reasons)

1. Continental Glaciations

more ice = lower sea level

2. Plate Tectonics

Fast spreading rate = high sea level

Slow spreading rate = low sea level

(affects the shape of ocean basins)

Seismic Sequence Stratigraphy

Principle 2

Eustatic Sea Level Changes (Local Reasons)

- Transgression in one place while regression in another
- Local mountain uplift or crustal subsidence
- Very rapid influx of sediment or erosion.

Seismic Sequence Stratigraphy

Principle 3 Stratigraphy

Stratigraphy is the discipline that studies the vertical and lateral relationships of sedimentary rocks.

A. Lithostratigraphy deals with rock packages, their facies relationships and organizations into mappable units (formation, group,..etc.).

B. Biostratigraphy is the study of correlative units (zones) based on fossil content.

Seismic Sequence Stratigraphy

Principle 3 Stratigraphy

C. Chronostratigraphy deals with rocks deposited with a particular interval of time.

D. Magnetostratigraphy deals with signature of the magnetic polarity reversals in sedimentary successions and layered volcanic rocks.

E. Seismic stratigraphy was developed utilizing distribution of discontinuities to subdivide sedimentary rocks.

F. Allostratigraphy correlation based on bounding surfaces

Seismic Sequence Stratigraphy

Principle 3 Stratigraphy

Fundamental Stratigraphy Terminologies:

1. Concept of high and low resolution sequence stratigraphy;
2. Concept of base level;
3. Concept of base level cycle;
4. Major controlling factors of base level cycle.

Fundamental Principles:

1. Accommodation to sediment supply (A/S) ratio;
2. Sediment volume partitioning;
3. Facies differentiation.

Fundamental Methods:

1. Base level cycle recognition;
2. Base level cycle correlation.

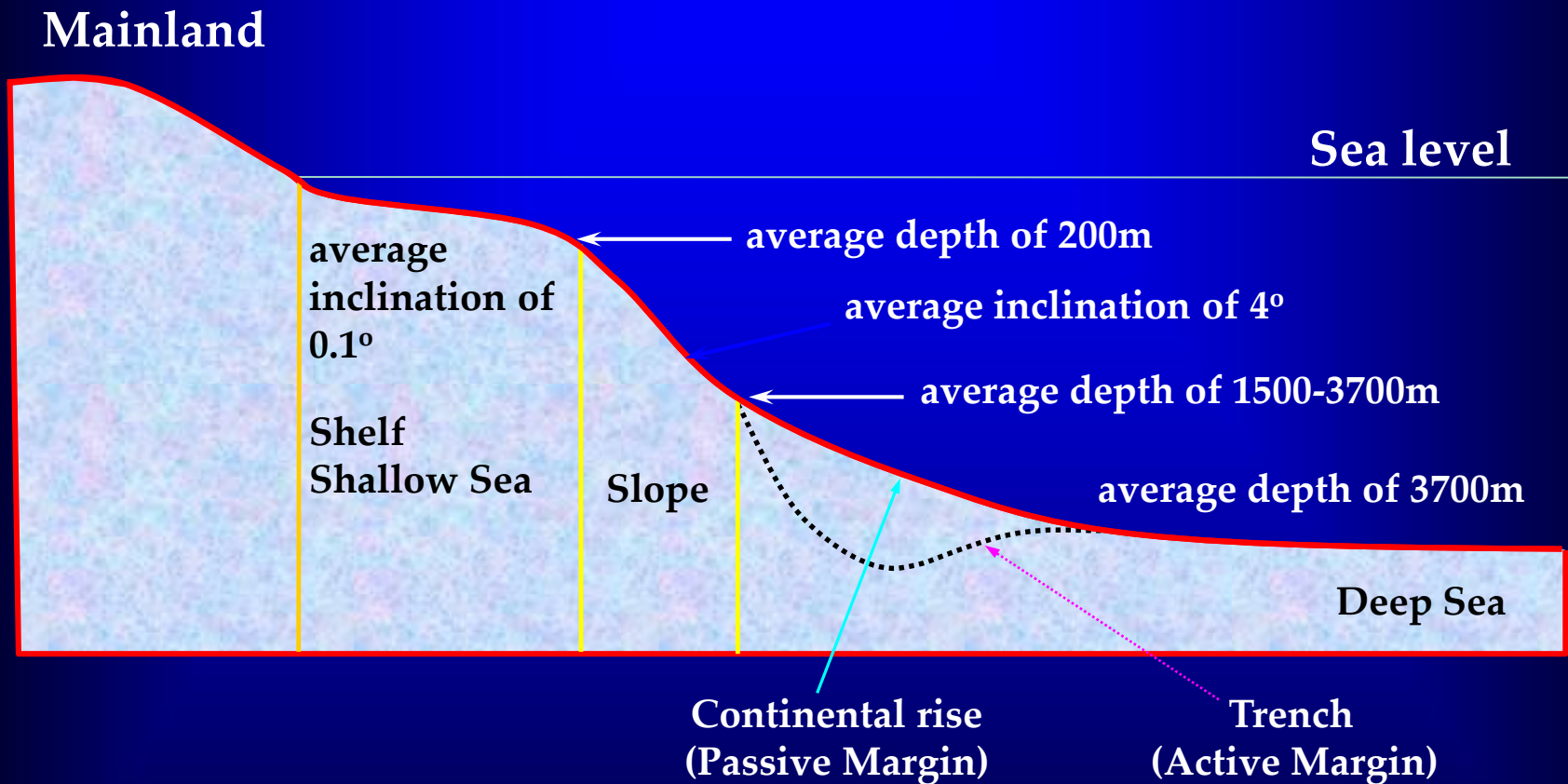
Seismic Sequence Stratigraphy

1. Concept of low resolution and high resolution sequence stratigraphy

◆ **Low-resolution sequence stratigraphy** is the concept of stratigraphic cycles developed using seismic data which has a relatively coarse resolution of many tens to hundreds of meters. Seismic-based stratigraphy has been termed 'low-resolution sequence stratigraphy'.

◆ **High-resolution sequence stratigraphy** integrates observations at a log, core, outcrop and high resolution seismic profiles, with high-resolution sequence stratigraphic theory, precise stratigraphic recognition and correlation techniques, to construct the high resolution stratigraphic architecture of regional, oilfield, reservoir scale.

Seismic Sequence Stratigraphy



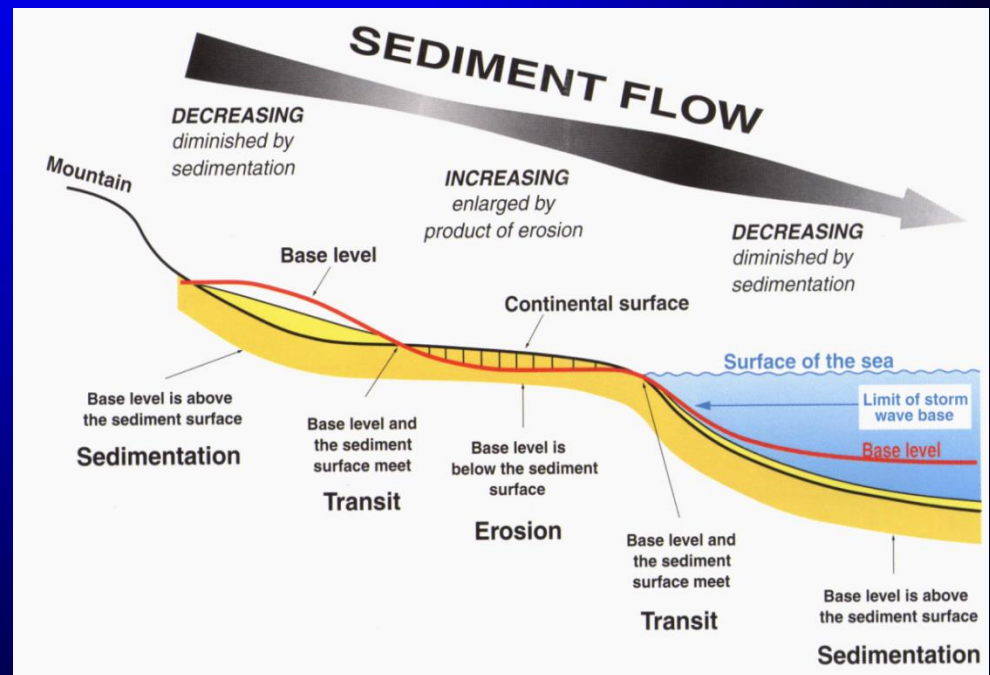
Tectonic Units of Continental Margin

Seismic Sequence Stratigraphy

2. Concept of Base level

- Base level is a Potentiometric Energy Surface, and the equilibrium surface below which sediment settles and above which erosion occurs. This does not correspond exactly to sea level, even at the shoreline.
- It is a surface of equilibrium between erosion and deposition.
- Base level is an irregular surface whose intersection with the earth's surface determines the areas under erosion, sedimentation, transit.

BASE LEVEL, which separates deposition zone from erosion zone (Wheeler, 1964)



Seismic Sequence Stratigraphy

3. Concept of Base level Cycles

- Base-level Cycles are the metronome of stratigraphy and are recorded as stratigraphic cycles of unidirectional increases followed by decreases of the accommodation to sediment supply (A/S) ratio.
- A complete base-level cycle consists of one base-level rise hemi-cycle and one base-level fall hemi-cycle.
- Base-level transit cycle refers to the base-level surface fluctuation downward or upward across the earth's surface.
- Base-level turnaround point is the turn position of base-level rise-to-fall or base-level fall-to-rise.

Seismic Sequence Stratigraphy

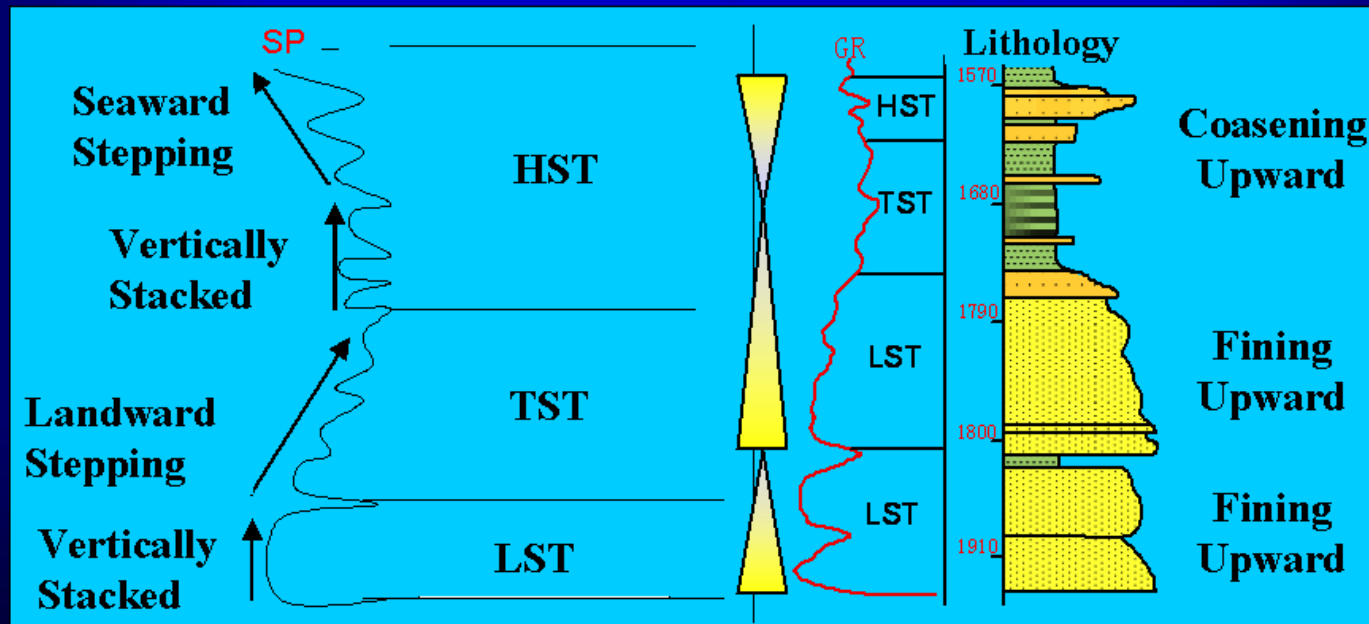
3. Concept of Base level Cycles

- Cycle symmetry refers to the proportion of base-level fall and rise time that is preserved as rock.
- A symmetrical stratigraphic cycle contains approximately equal thicknesses of sediment accumulated during base-level-rise and base-level-fall time.
- An asymmetrical stratigraphic cycle consists of rock that accumulated dominantly during either base-level rise or fall.

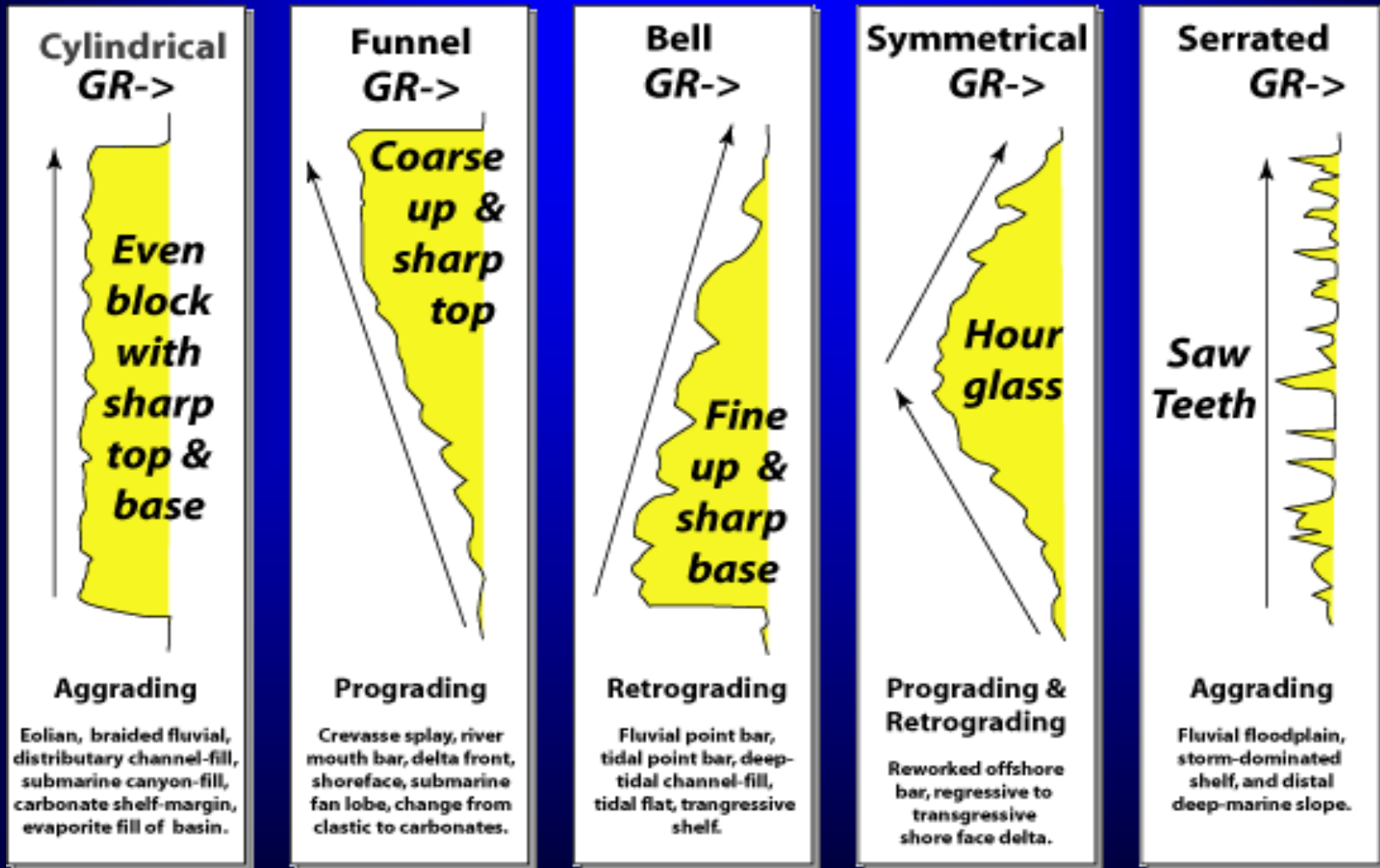
● *Base level cycle recognition markers-Well Logs*

To well log, the interpretation rules are based on the shape of the log curve and lithological combination and succession, as follows:

- (1) sharp lithological contacts (e.g. clean sandstone truncating underlying shale);
- (2) log curve shape changes (e.g. GR, SP log curves, turnaround point of base-level falling to ascending with high GR and SP curve value; turnaround point of base-level ascending to falling with low GR and SP curve value;)
- (3) weathering and denudation surfaces, and scouring surfaces;
- (4) transitional surfaces between the ascending and falling cycles.



General Gamma Ray Response to Variations in Grain Size



General Gamma Ray Response to Variations in Grain Size



cylindrical or block shape, with low gamma and sharp boundaries and no internal change:
this trend is predominant in fluvial channel sands, turbidites (typically with greater range of thickness), and aeolian sands. Evaporites also can have a cylindrical gamma trend.

General Gamma Ray Response to Variations in Grain Size



funnel shape, a gradual upward decrease in gamma response. In shallow marine settings, this trend reflects a change from shale-rich into sand-rich lithology and upward increase in depositional energy with shallowing-upward and coarsening. In deep marine settings, this trend reflects an increase in the sand contents of turbidite bodies. This trend also may indicate gradual change from clastic to carbonate deposition.

General Gamma Ray Response to Variations in Grain Size



bell shape, a gradual upward increase in gamma response: This trend may reflect upward fining (eg: a lithology change from sand to shale) or upward fining of sand beds in a thinly interbedded sand-shale unit.

This trend usually implies a decrease in depositional energy. In a non-marine setting, fining upward is predominant within meandering or tidal channel deposits with an upward decrease in fluid velocity within a channel (coarser sediments at base of channel).

In a shallow-marine setting, this trend usually reflects an upward deepening and a decrease in depositional energy (shoreline retreat).

In deep-marine settings, this trend reflects waning of submarine fans (reducing of sand contents).

General Gamma Ray Response to Variations in Grain Size



Symmetrical, with gradual decrease then gradual increase in gamma response: this is usually the result of progradation and retrogradation of clastic sediments.

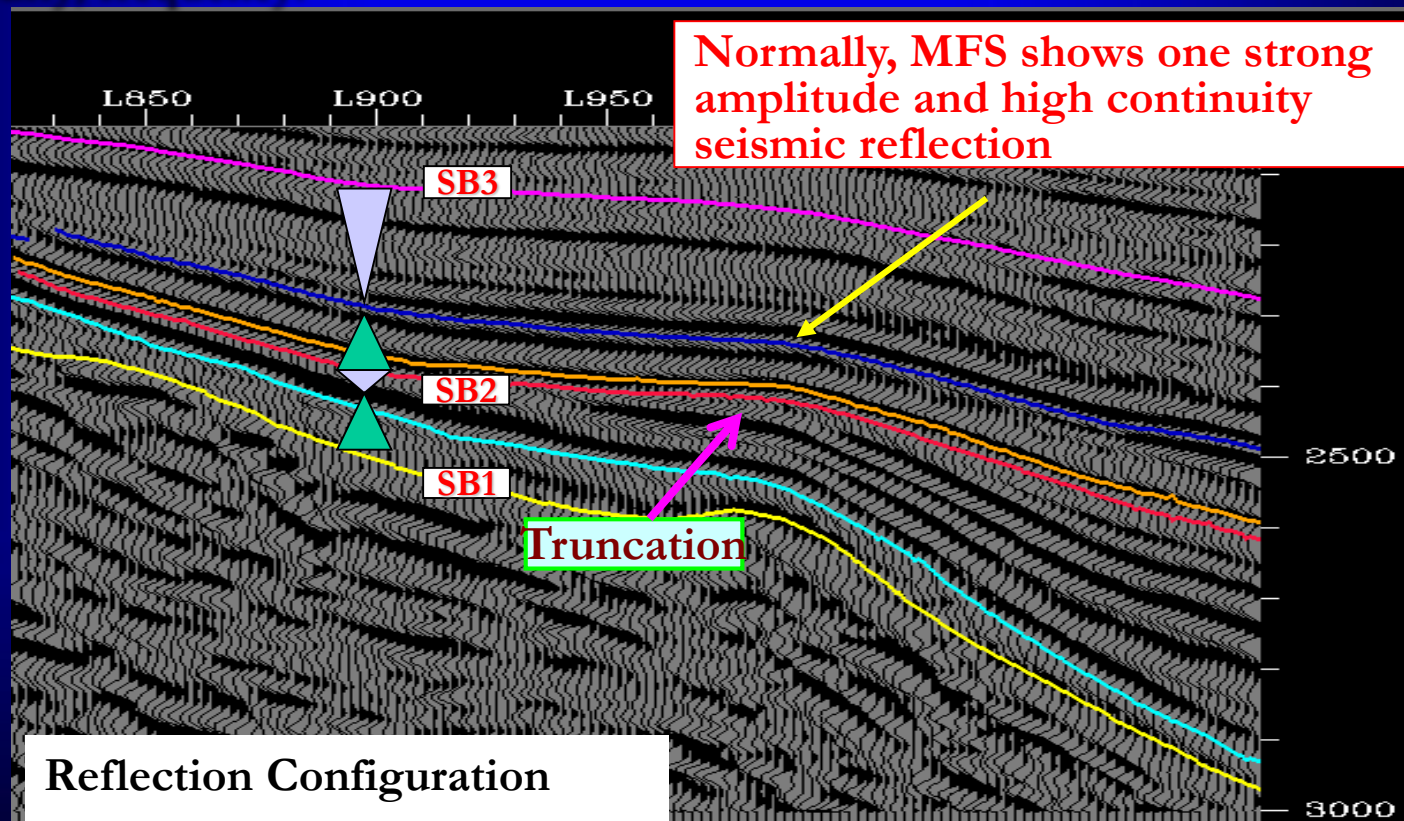
General Gamma Ray Response to Variations in Grain Size



this trend represents aggradation of shales or silts

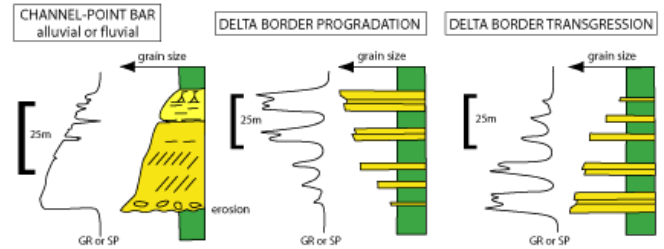
Base level cycle recognition markers seismic profile

- Seismic reflection is used to recognize the long-term base-level cycles.
- Seismic reflection parameters: internal reflection configuration, external form, amplitude, continuity, frequency.

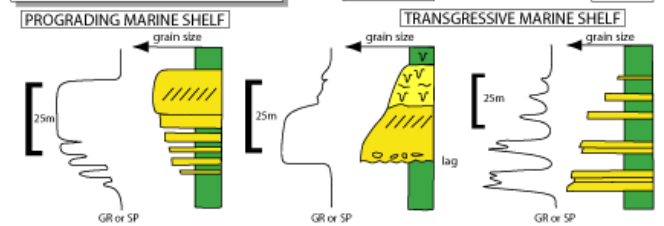


Gamma Ray Log Response & Depositional Setting

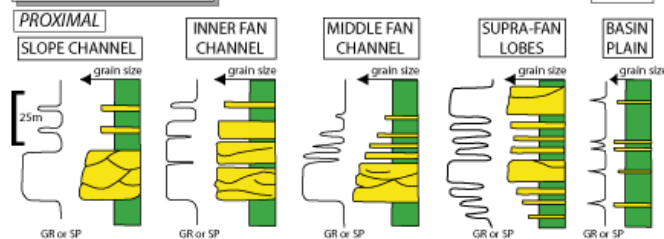
DELTAIC & FLUVIAL SETTINGS



CLASTIC MARINE SETTINGS



DEEP SEA SETTINGS



C. G. St. C. Kendall 2003 (modified from Malcolm Rider 1999)

Seismic Sequence Stratigraphy

Principle 3

Stratigraphy

Eight Stratigraphic Concepts

- 1) Clastic sediments are deposited in layers, called strata or beds. This layering results from the tendency of water or wind spreading similar sediment types in a relatively thin sheet over a broad area during a period of similar environmental conditions. When environmental conditions change at the site of deposition, several things may happen:
 - Different sediment types may be deposited on top of the previous layer.
 - There may be a period where no sediments are deposited.
 - The original layer may be eroded.

In any event, because of their common depositional environment, sediment types tend to be much more similar within layers than between layers.

Seismic Sequence Stratigraphy

Principle 3 Stratigraphy

Eight Stratigraphic Concepts

- 2) Although sediments tend to be more similar within a layer than across layers, this lateral continuity has finite limits. A particular layer may be thin and pinchout laterally, leaving no particular record of the time of deposition in the pinchout region. The sediment types characterizing the layer may gradually grade laterally into other sediment types within the same layer, suggesting that depositional environments also change really in a gradual fashion.
- 3) Certain combinations of depositional environments foster abrupt discontinuity of layers of similar sediment types. For instance, river laid sands and shales are commonly discontinuous because of repeated channeling and overbank flooding. Other environments lead to more continuous layers: pelagic shales in deep marine basins are a good example.

Seismic Sequence Stratigraphy

Principle 3 Stratigraphy

Eight Stratigraphic Concepts

6) Well log correlation of chronostratigraphic layers is very dependent on the continuity of sediment types within strata. Seismic correlation, fortunately, gives a much better view of large scale chronostratigraphic layering in discontinuous sediments than do well logs, but seismic resolution of individual layers is limited when compared to well logs. Thus the two media should be used as mutually helpful tools for chronostratigraphic correlation. Detailed ties of individual thin layers from logs to seismic sections is a critical step in the use of the two media.

Seismic Sequence Stratigraphy

Principle 3 Stratigraphy

Eight Stratigraphic Concepts

- 7) Stratal surfaces typically represent relatively small time-gaps. If the time-gap is large, the surface is called an unconformity. Such a time-gap often receives the name of hiatus, indicating that it might have represented the time-gap.
- 8) All unconformities somewhere have a minimum time-gap, often at the slope portion of the basin. It is this minimum gap-time which is the appropriated age designation for the unconformity. An understanding of the chronostratigraphic correlation sections (see later) are essential to understand the relationships of physical stratigraphy in a framework of geologic time.

Sequence Stratigraphy

Principle 3

Sequence Definition

Mitchum (1987) defines a sequence as a conformable succession of genetically related strata bounded by unconformities and their correlative conformities.

A method to impose the dimension of time on the relationships of rock units in space (area and depth) By understanding how rock units are related in time and space, we can better interpret how they are connected as oil and gas reservoirs

Sequence Stratigraphy

Principle 3

Sequence Definition

- Sequences - Groups of formations bounded by erosional surfaces
 - 17,000 formations within the U.S.
 - Each formation is distinct in time, place and rock type
 - Sequences of formations relate changes in depositional environments

Seismic Sequence Stratigraphy

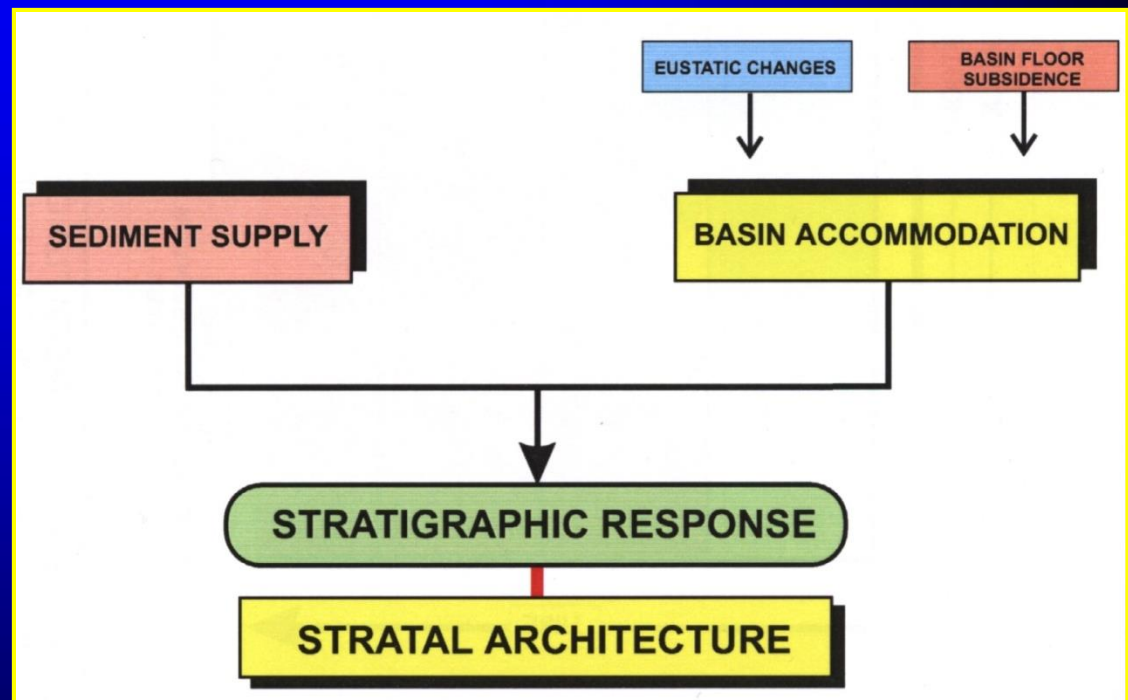
Principle 3

Sequence Definition

- Stratigraphic signature results from interaction of tectonic, eustatic, sedimentation and climatic processes.
- Tectonic and eustatic processes combine to cause relative changes of sea level which control the space available for sediments (accommodation space).
- Tectonism and climate control the amount and type of sediments deposited.

Seismic Sequence Stratigraphy

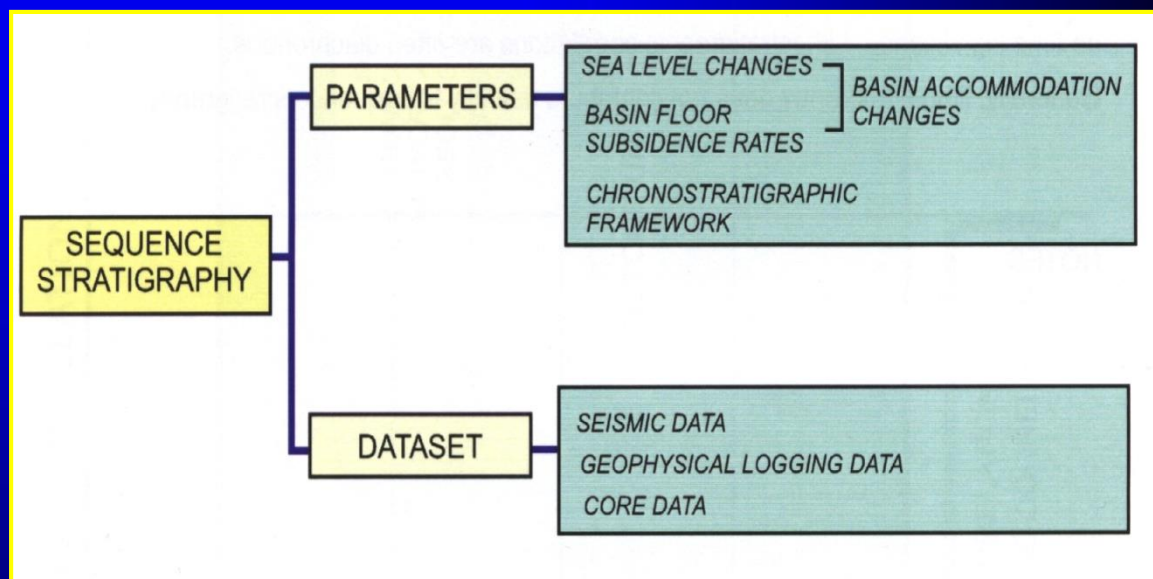
Principle 3 Sequence Definition



Stratal architecture of stratigraphic response is a product between changes in basin accommodation and sediment supply (Posamentier and James, 1993).

Seismic Sequence Stratigraphy

Principle 3 Sequence Definition



Ingredients for sequence stratigraphic analysis are parameters for basin accommodation changes and a chronostratigraphic framework.

Sea level fluctuations are the major controlling mechanism in producing sequence architecture.

Seismic Sequence Stratigraphy

Accommodation space What is it?

The space available for potential sediment accumulation...area below base level (Jervy, 1988).

A combination of subsidence, eustasy, & climate

How is it Recognized?

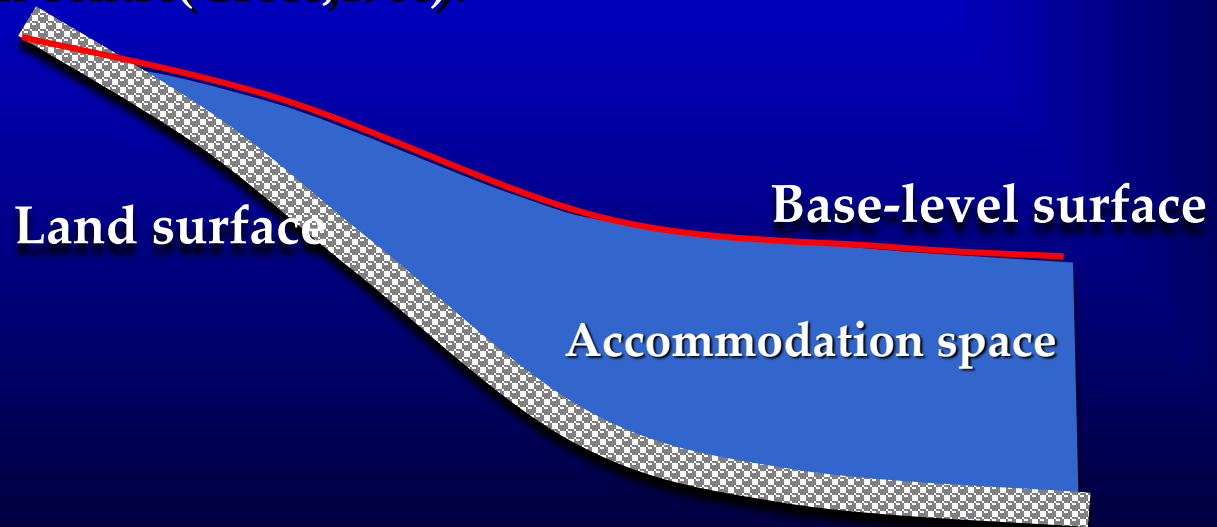
Stratal geometries (aggradation, progradation, onlap, etc.)

Facies distribution (basinward/landward shifts of facies, coal geometry, fluvial channel amalgamation, etc.)

Seismic Sequence Stratigraphy

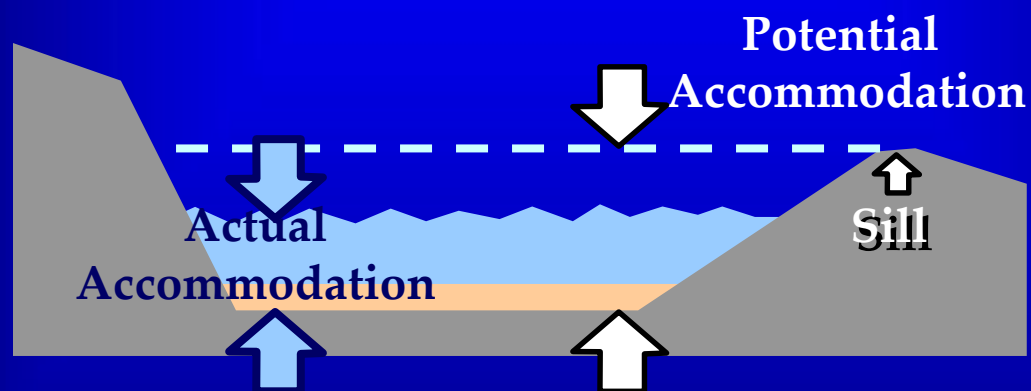
Accommodation space

It is the **space** (volume) between the earth's surface and base level surface which is available for sediment accumulation. It **varies** geographically during base-level cycles such that there are geographic **shifts** in sites of higher and lower accommodation toward and away from the basin centre (Cross, 1988).

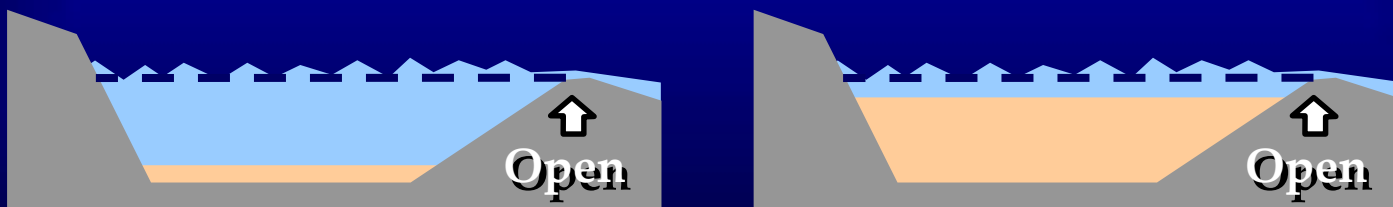


Seismic Sequence Stratigraphy

Potential Accommodation space



Filled with combination of Sediment & Water:



Seismic Sequence Stratigraphy

Sediment supply :

- Sediment supply is an important variable in sequence stratigraphic analyses, and it refers to the amount (or flux) and type (grain size) of sediment that is supplied from source areas to depositional areas by various transport agents, including gravity, water, and wind.
- Sediment supply is primarily a by-product of climate and tectonism. A wetter climate increases the amount of sediment supply, via increased efficiency of weathering and erosion, and so does the process of tectonic uplift via source area rejuvenation.
- Sediment supply is critical to the stratigraphic architecture of any sedimentary basin, as it is one of the fundamental variables that determine the type of depositional trends in all fluvial to marine environments

Accommodation to Sediment Supply (A/S) ratio

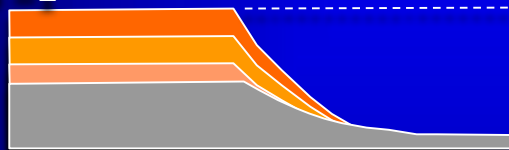
- The sequence stratigraphic architecture is controlled by the interplay between the rate of change in accommodation and the rate of sediment supply.
- Base level always fluctuates all the time. When base level is above the earth's surface and continues rise, the new accommodation space are created for the sediment to fill, but the actual rate of sediment accumulation is also governed the rate of sediment supply.
- Accommodation to sediment supply (A/S) ratio control on the actual degree of sediment accumulation and preservation, internal configuration of sediment.
- The balance of sediment supply and accommodation space controls whether facies belts prograde basinward or retrograde landward.

Seismic Sequence Stratigraphy

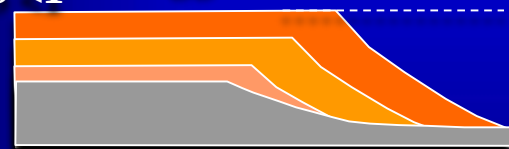
Principle 3

Sequence Definition

$$A/SS = 1$$

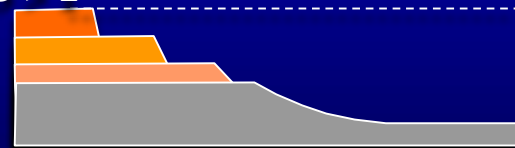


$0 < A/SS < 1$ Aggradation



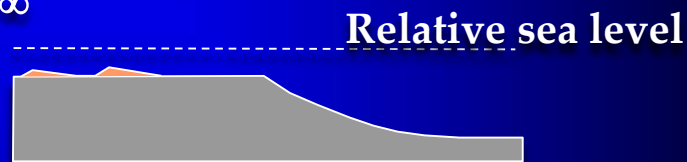
Prograding Aggradation

$$A/SS > 1$$



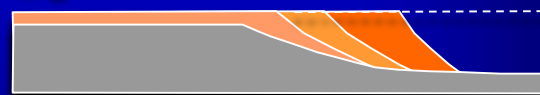
Backstepping
Retrograding

$$A/SS \rightarrow \infty$$



Drowning

$$A/SS \approx 0$$



Prograding

$$A/SS < 0$$



Exposure

A = Accommodation (Eustatic changes & Subsidence)

SS = Sediment Supply

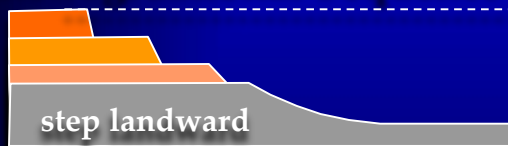
Seismic Sequence Stratigraphy

Principle 3 Sequence Definition

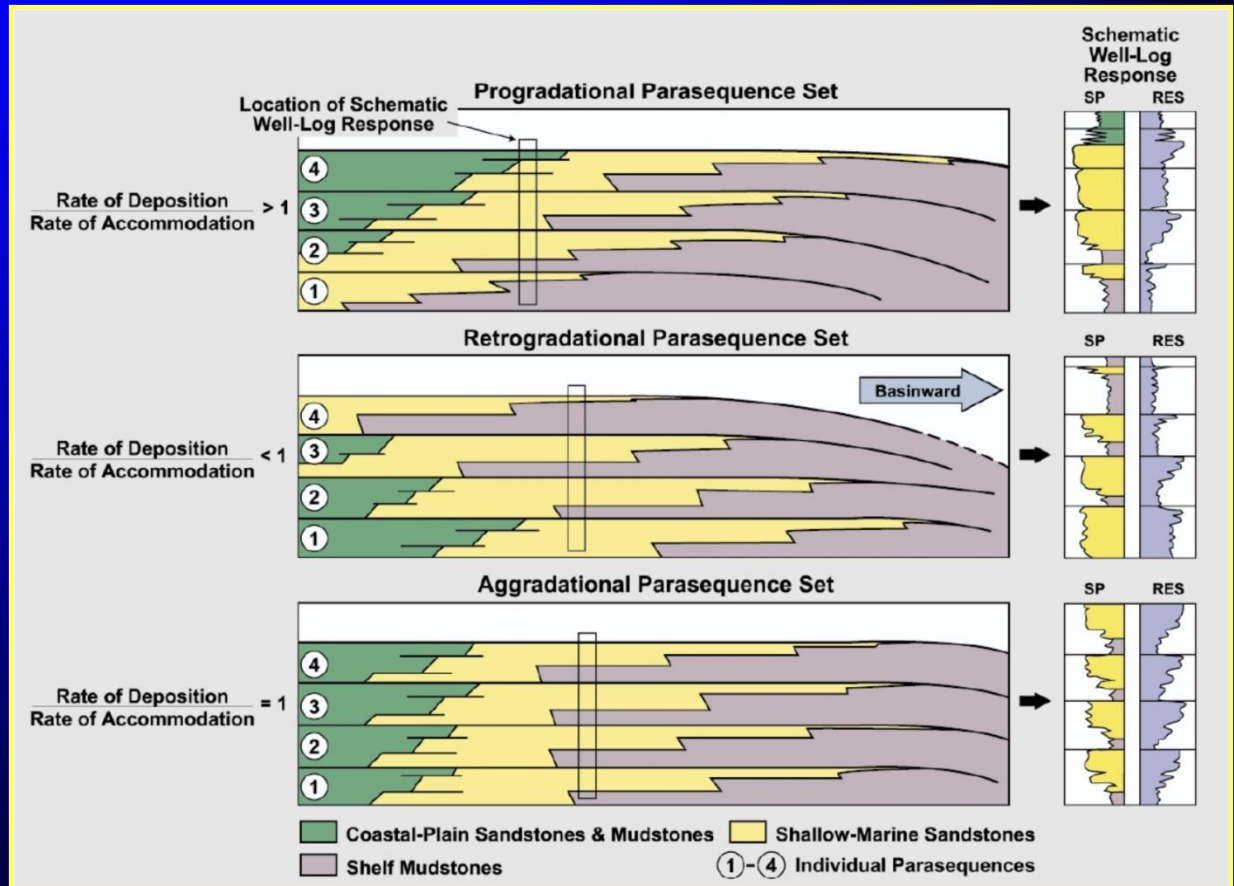
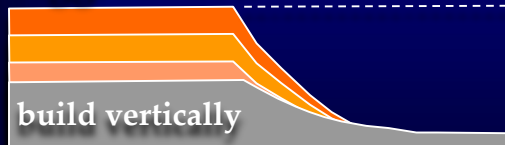
Progradational Sequence



Retrogradational Sequence



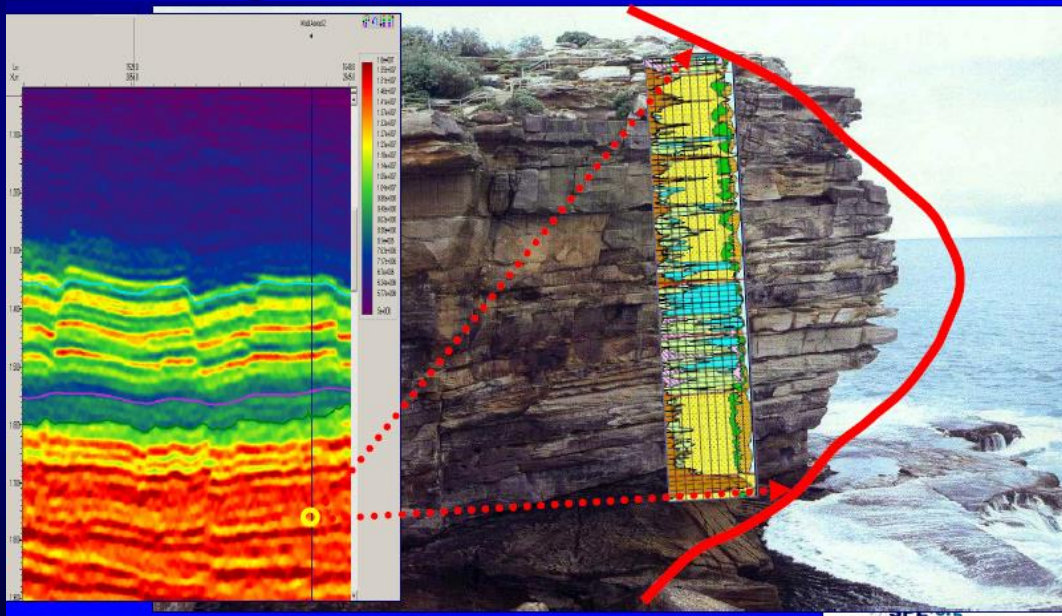
Aggradation



Seismic Sequence Stratigraphy

Sequence Definition -Scale Limitation

There are significant differences in scale between the features that may be detected in seismic data, the features that are detectable with well logs, and the outcrop-scale features that can compartmentalize reservoirs. Seismic interpreters need to be aware of these differences .



what can be
identified on
seismic profiles
is system tracts

Seismic Sequence Stratigraphy

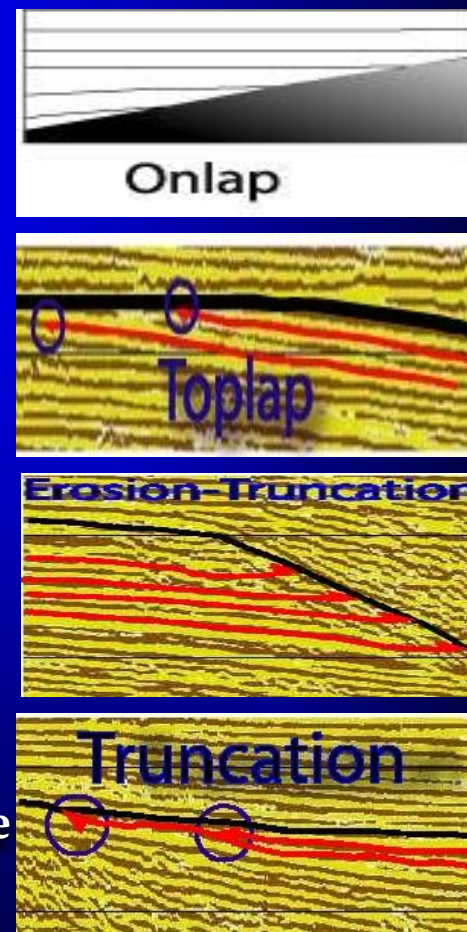
Terms to Define – Systems Tracts

- **Falling Stage Systems Tract (FSST)**
- **Lowstand Systems Tract (LST)**
- **Transgressive Systems Tract (TST)**
- **Highstand Systems Tract (HST)**
- **Regressive System Tract**
- **Low-accommodation systems Tract**
- **High-accommodation Systems Tract**
- **Forced regression**
- **Normal regression**
- **Transgression**

Seismic Sequence Stratigraphy

Sequence Boundary SB

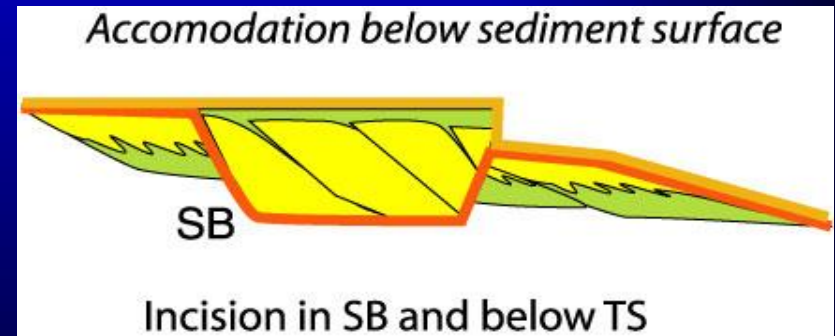
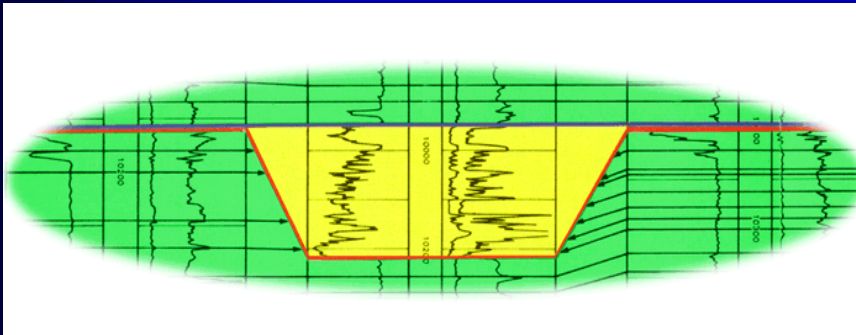
- Defined by erosion or truncation of underlying reflectors or the correlative conformity.
- Can be inferred from onlapping reflectors overlying a surface.
- Should the upper surface of a falling stage system tract be eroded when a shoreline is forced seaward (a forced regression!) by a drop in sea level (or base level) the interpretation of a sequence boundary is ambiguous



Seismic Sequence Stratigraphy

Sequence Boundary SB

Defined by erosion or incision of underlying flooding surfaces (mfs and TS)
Inferred from interruption in the lateral continuity of these surfaces



Seismic Sequence Stratigraphy

Sequence Boundary SB

Boundaries

Upper

Lower

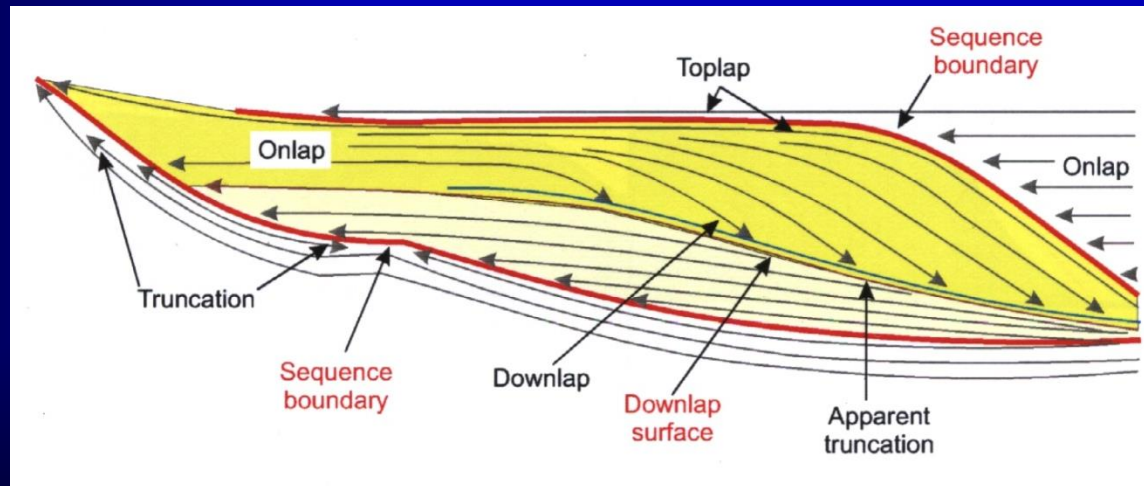
Toplap

Erosional Truncation

Baselap

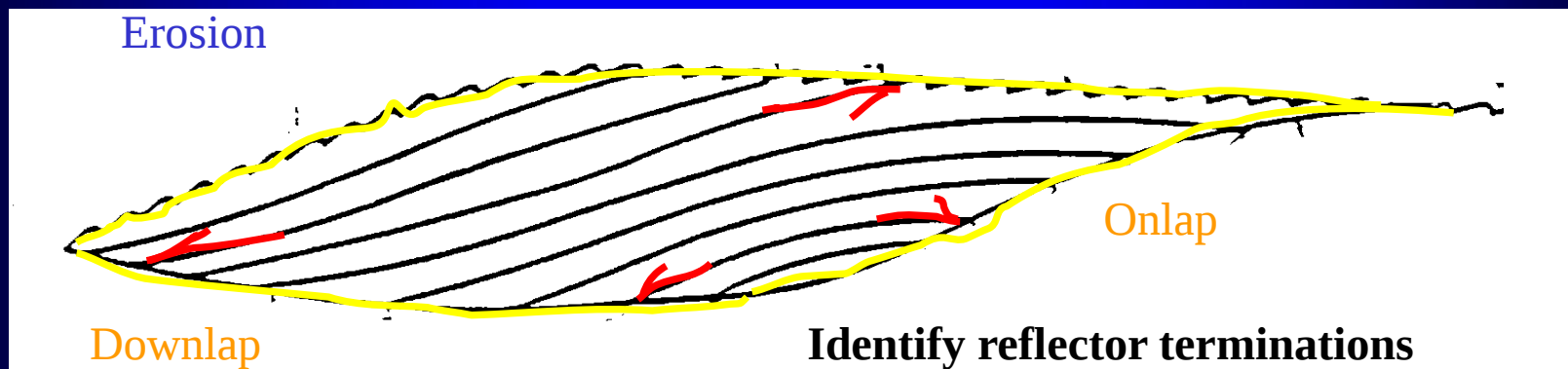
Onlap

Downlap

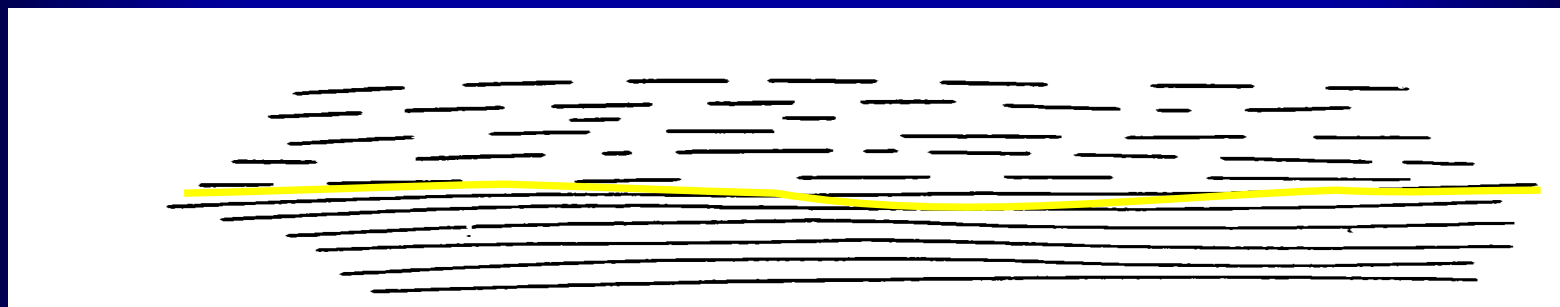


Seismic Sequence Stratigraphy

Sequence Boundary SB



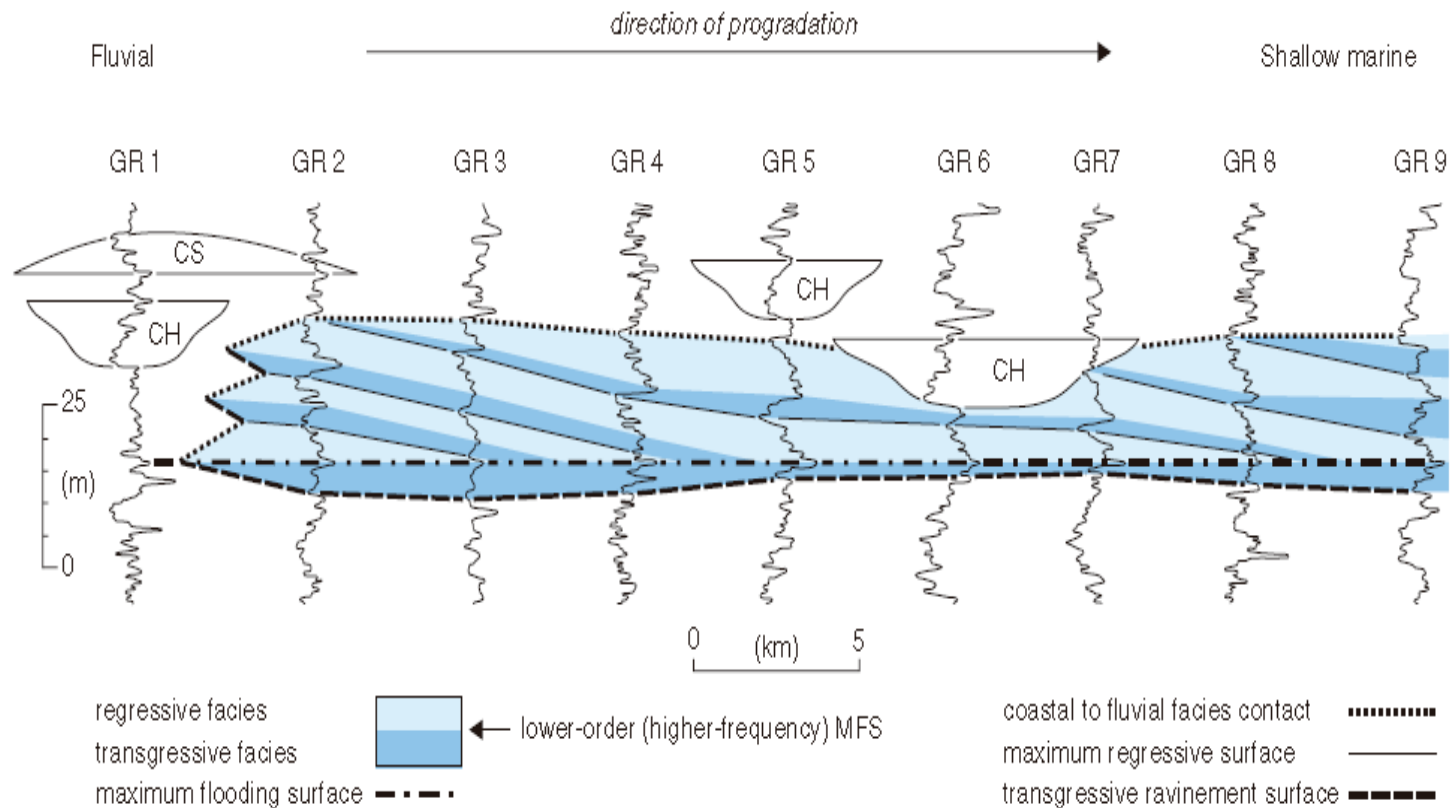
And/or



Abrupt vertical changes in reflection pattern

Seismic Sequence Stratigraphy

Sequence Boundary SB



Seismic Sequence Stratigraphy

Principle 4 System Tracts

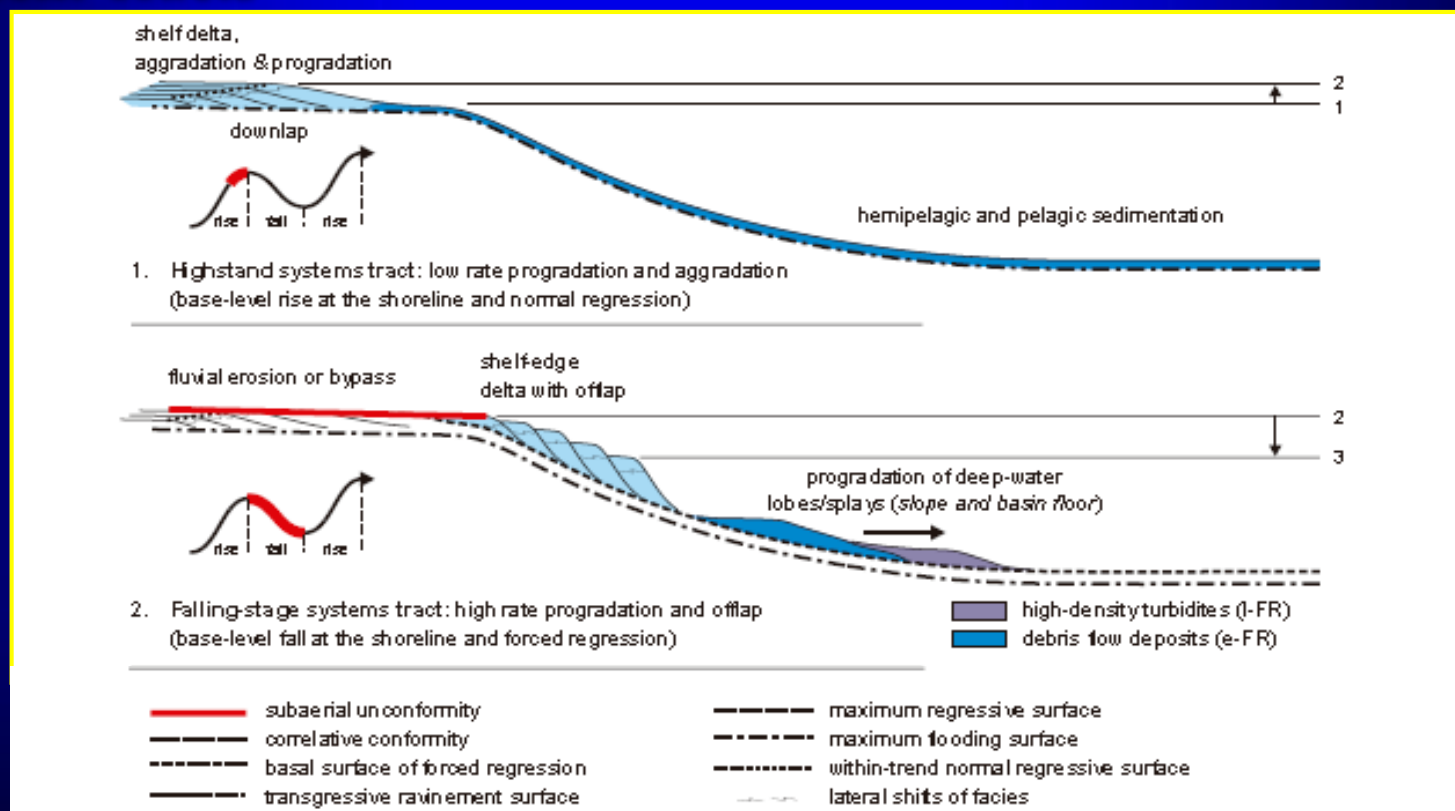
System Tracts:

Genetically associated stratigraphic units that were deposited during specific phases of the relative sea-level cycle (Posamentier et al, 1999)

- Lowstand system tract
- Transgressive system tract
- Highstand system tract

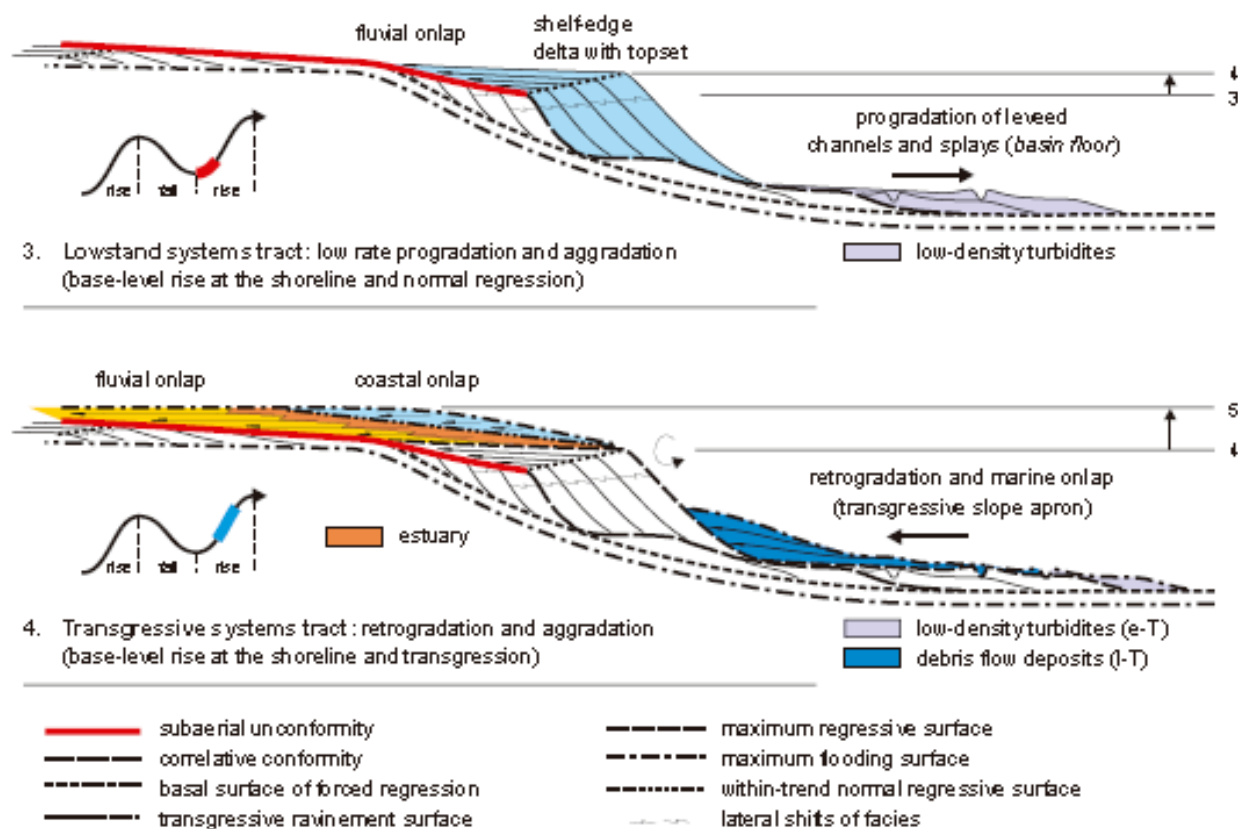
Seismic Sequence Stratigraphy

Principle 4 System Tracts



Seismic Sequence Stratigraphy

Principle 4 System Tracts

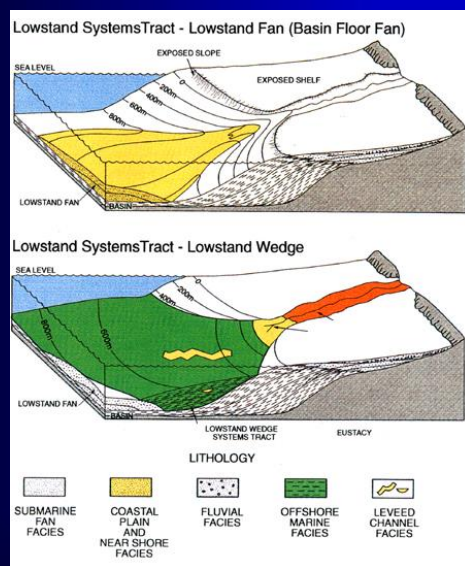
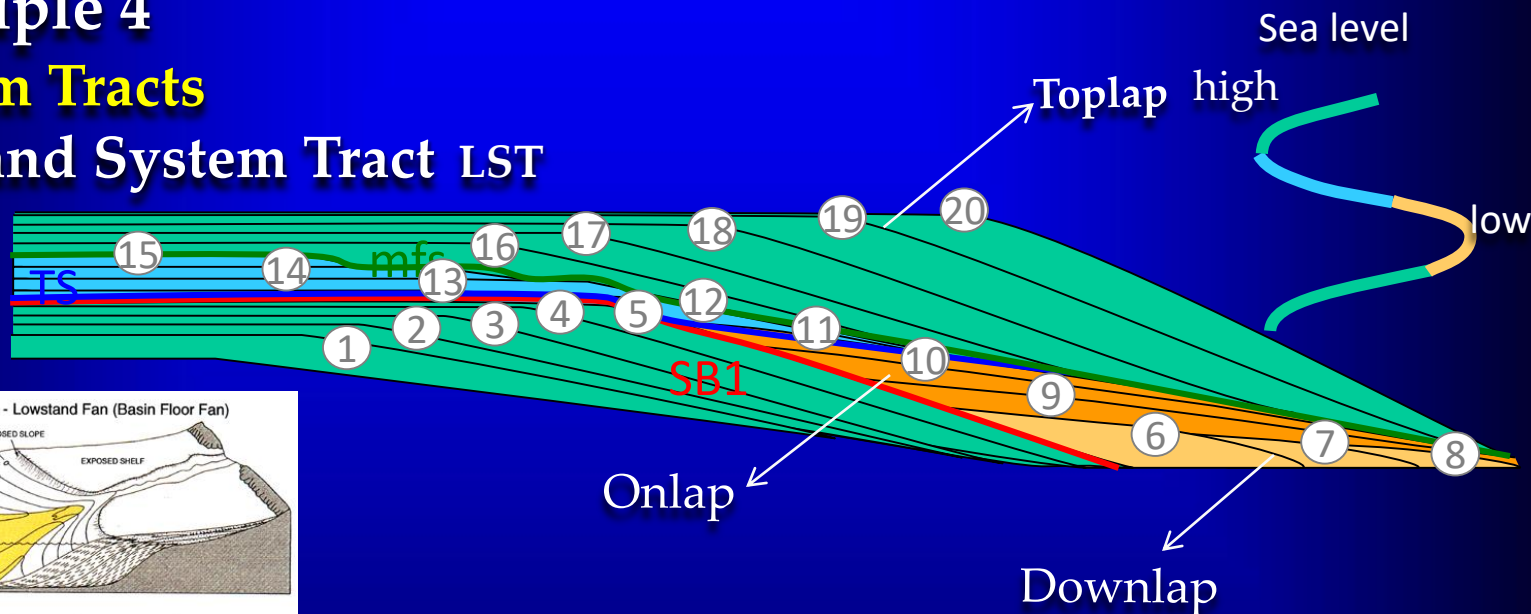


Seismic Sequence Stratigraphy

Principle 4

System Tracts

Low Stand System Tract LST



Early LST

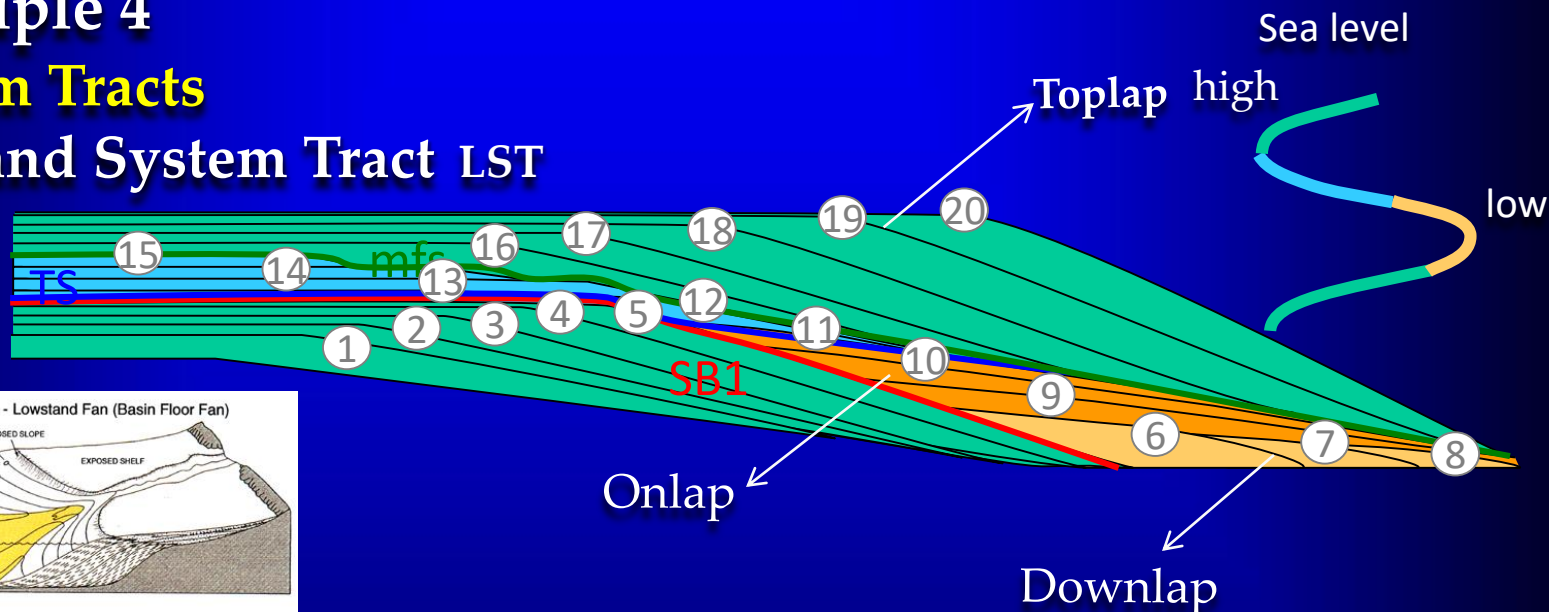
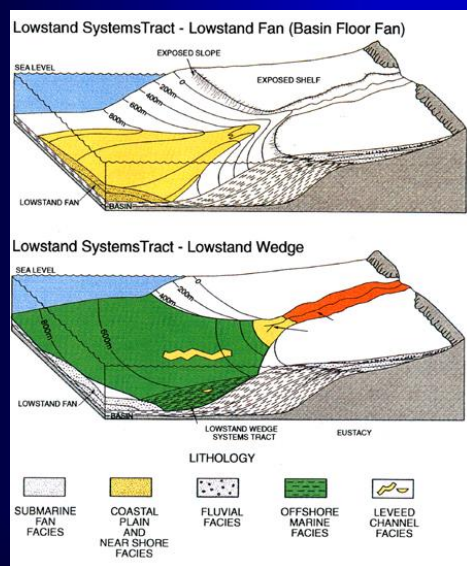
Falling sea level & high sedimentation
Produce forced regression & prograding Clinoforms

Seismic Sequence Stratigraphy

Principle 4

System Tracts

Low Stand System Tract LST



LST

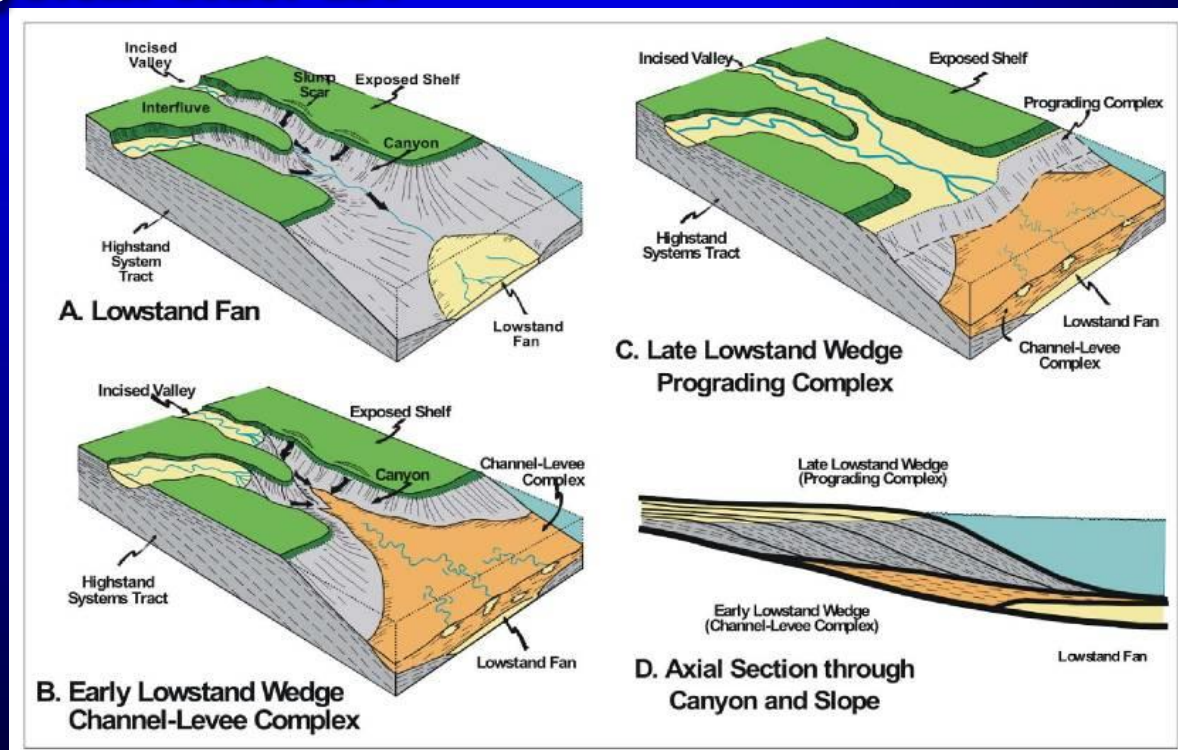
The lowstand systems tract is the set of depositional systems active during the time of relatively low sea level following the formation of the sequence boundary. If a distinct shelf-slope break exists and relative sea level has fallen sufficiently, the lowstand systems tract may include two distinct parts, the lowstand fan and the lowstand wedge.

Seismic Sequence Stratigraphy

Principle 4

System Tracts

Low Stand System Tract LST



Seismic Sequence Stratigraphy

Principle 4

System Tracts

Low Stand System Tract LST

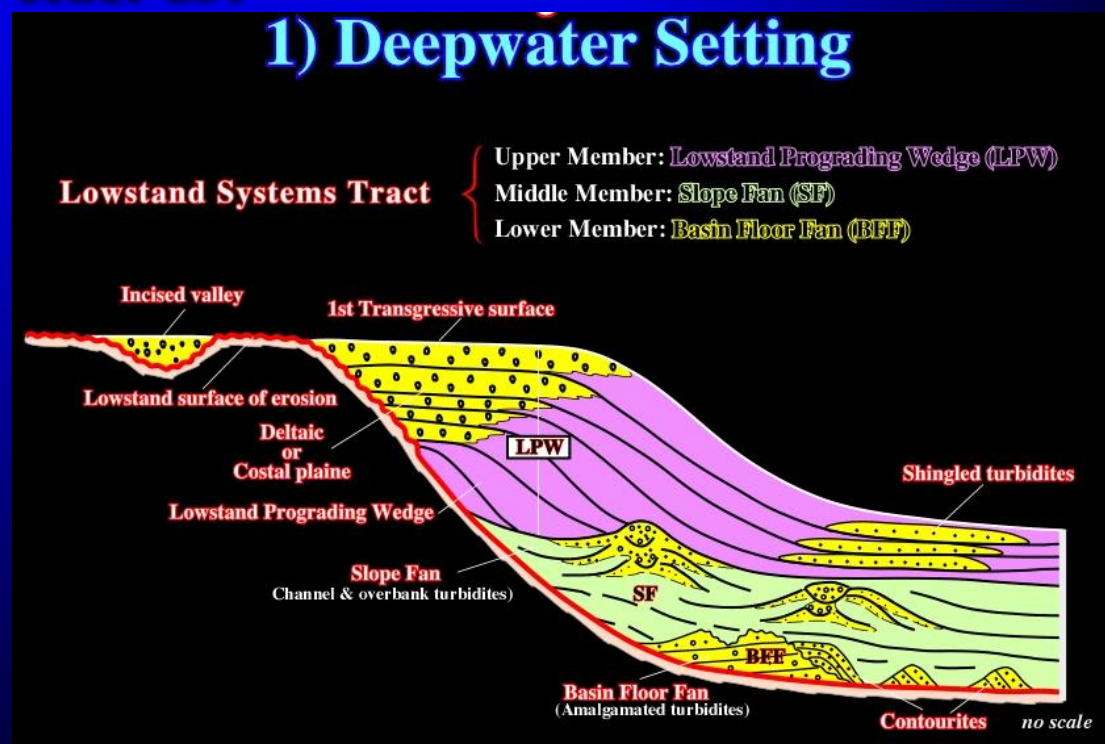
LST geological Settings:

Three geological settings can be recognized in lowstand systems tracts:

1-Deep-water setting.

2-Ramp setting

3-Growth-fault setting



Basics of Seismic Sequence Stratigraphy

Lowstand System Tract LST

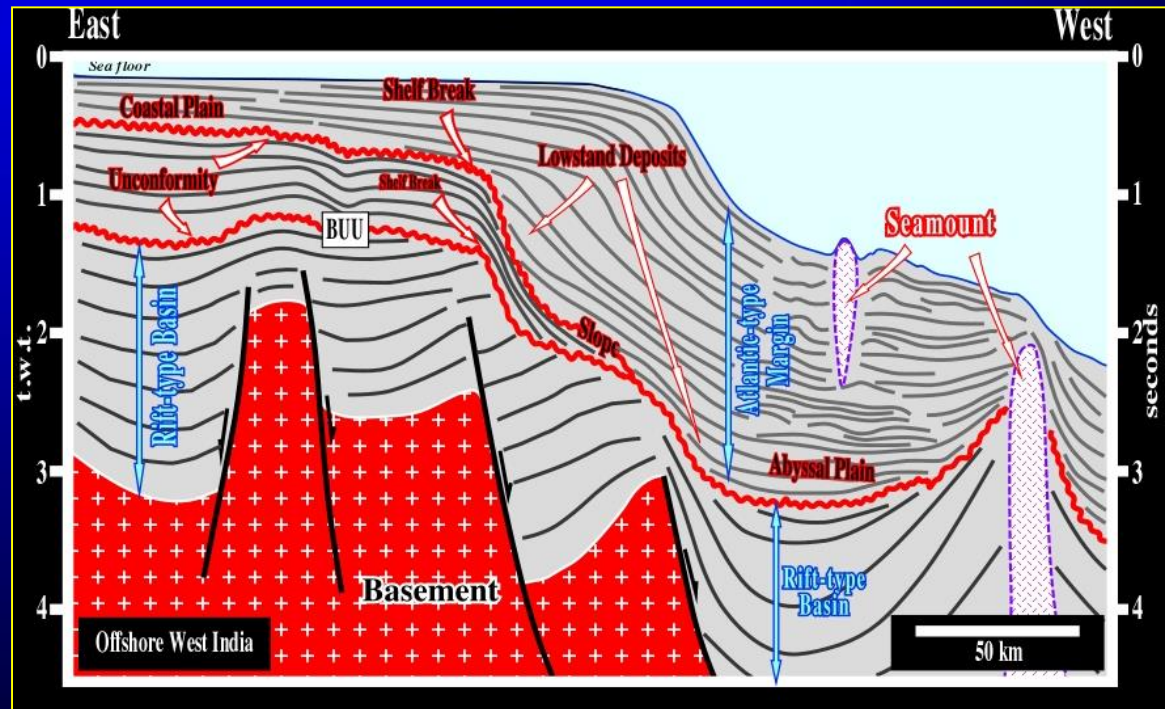
Principle 4

System Tracts

Low Stand System Tract LST

1-Deep-water setting.

Basin Floor Fan BFF



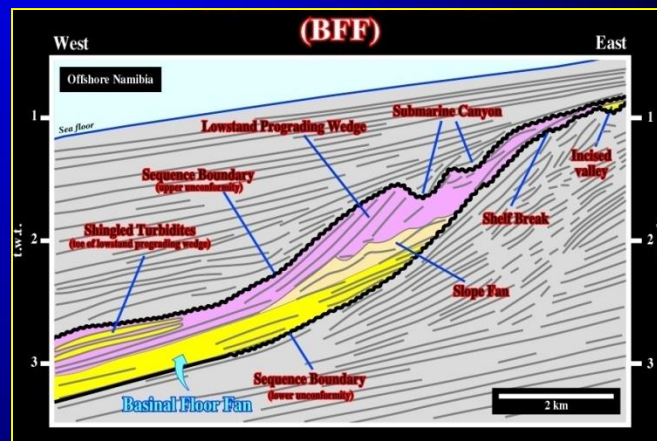
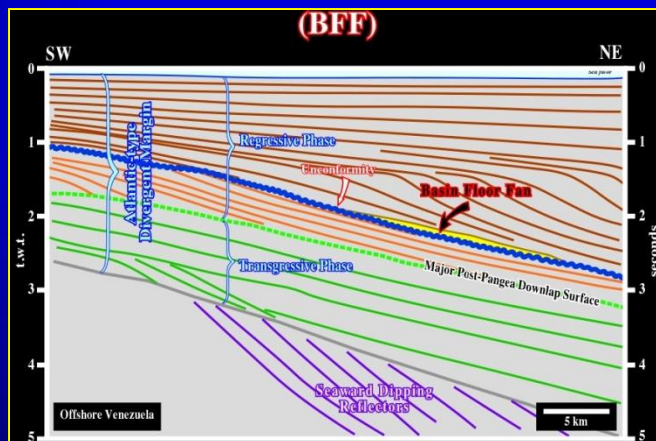
Seismic Sequence Stratigraphy

Principle 4

System Tracts

Low Stand System Tract LST

Basin Floor Fan BFF



Lowstand basin floor fans are associated with the time of rapid eustatic fall, when sea level falls below the shelf break and sediments are transported across the shelf in incised valleys and rapidly dumped into the basin.

2) Lowstand fan sand lobes may develop as relatively isolated lobes or as huge accumulations of virtually basinwide extend.

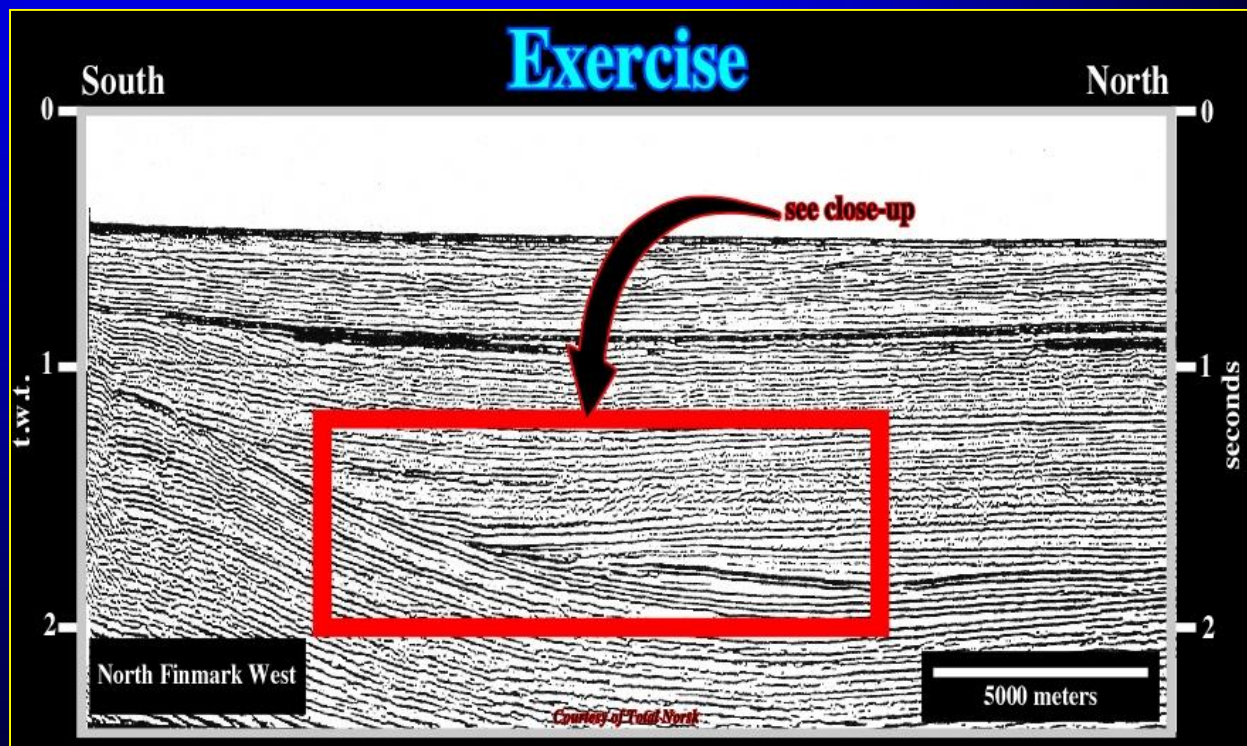
Seismic Sequence Stratigraphy

Principle 4

System Tracts

Low Stand System Tract LST

Basin Floor Fan BFF



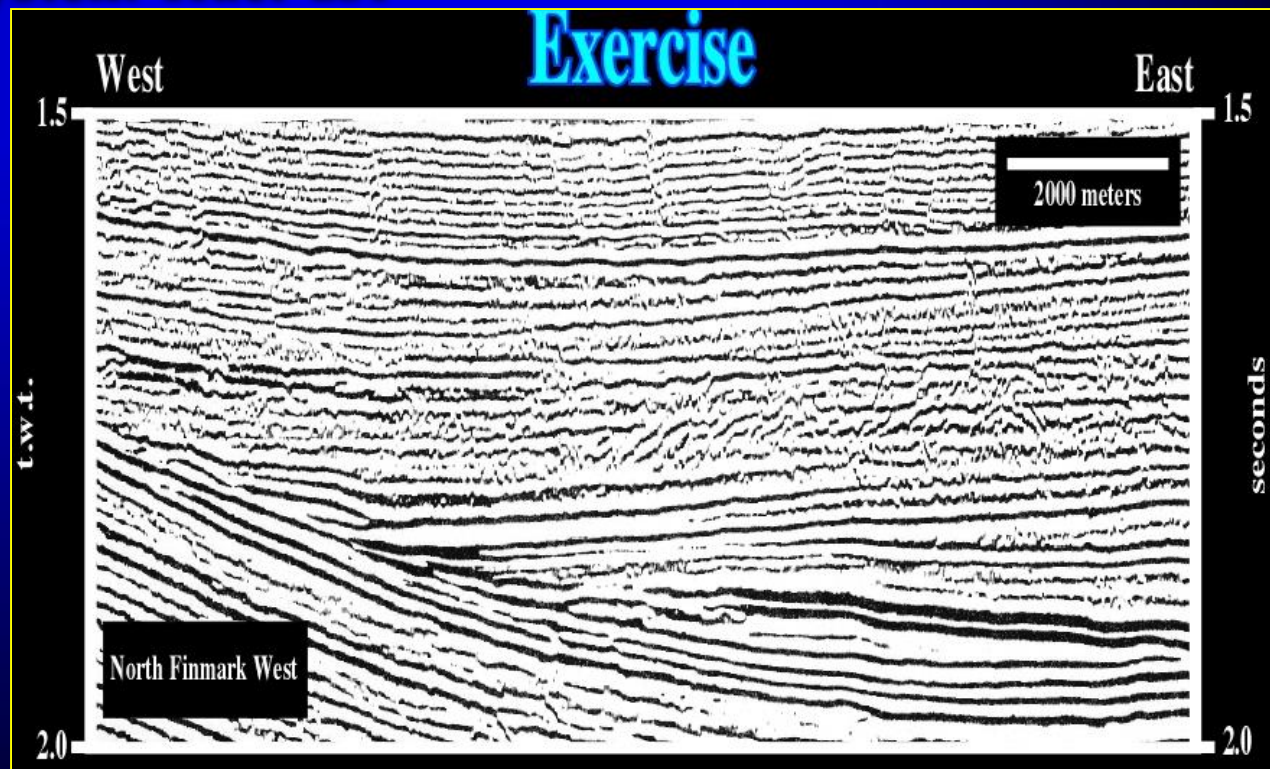
Seismic Sequence Stratigraphy

Principle 4

System Tracts

Low Stand System Tract LST

Basin Floor Fan BFF



Basics of Seismic Sequence Stratigraphy

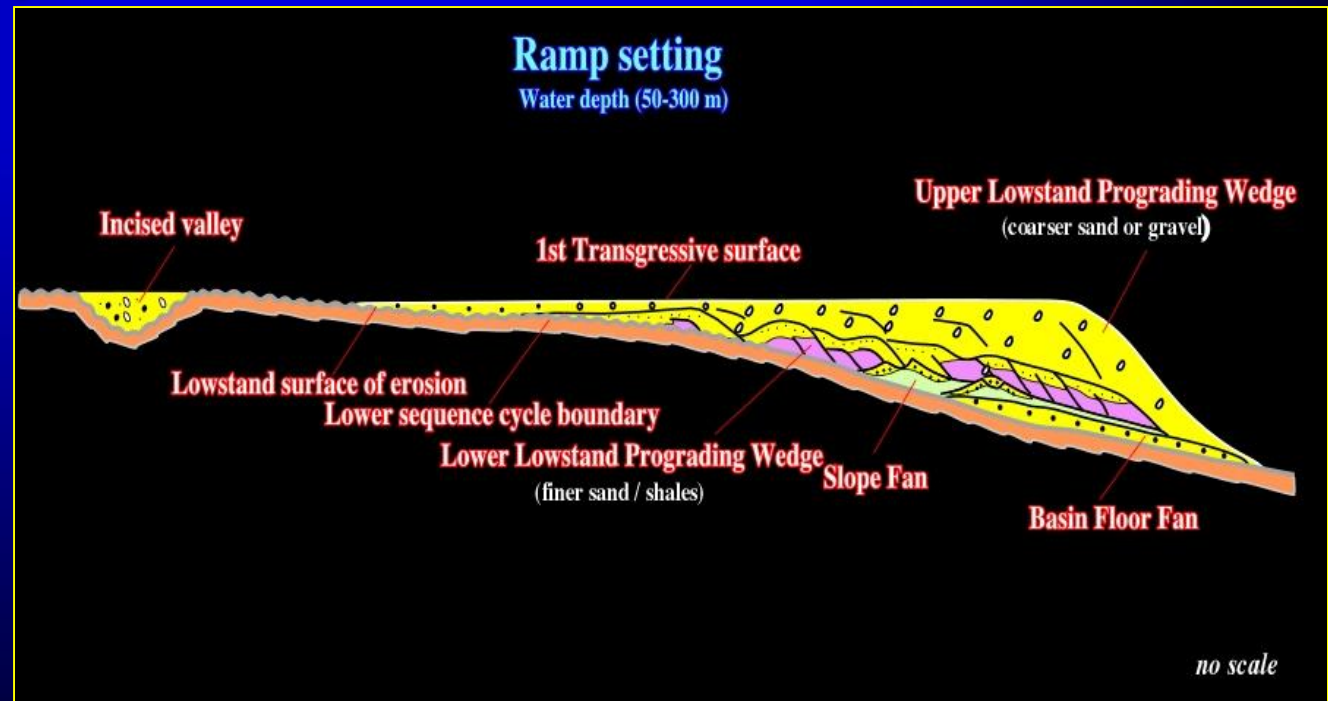
Lowstand System Tract LST

Principle 4

System Tracts

Low Stand System Tract LST

2-Ramp setting



Basics of Seismic Sequence Stratigraphy

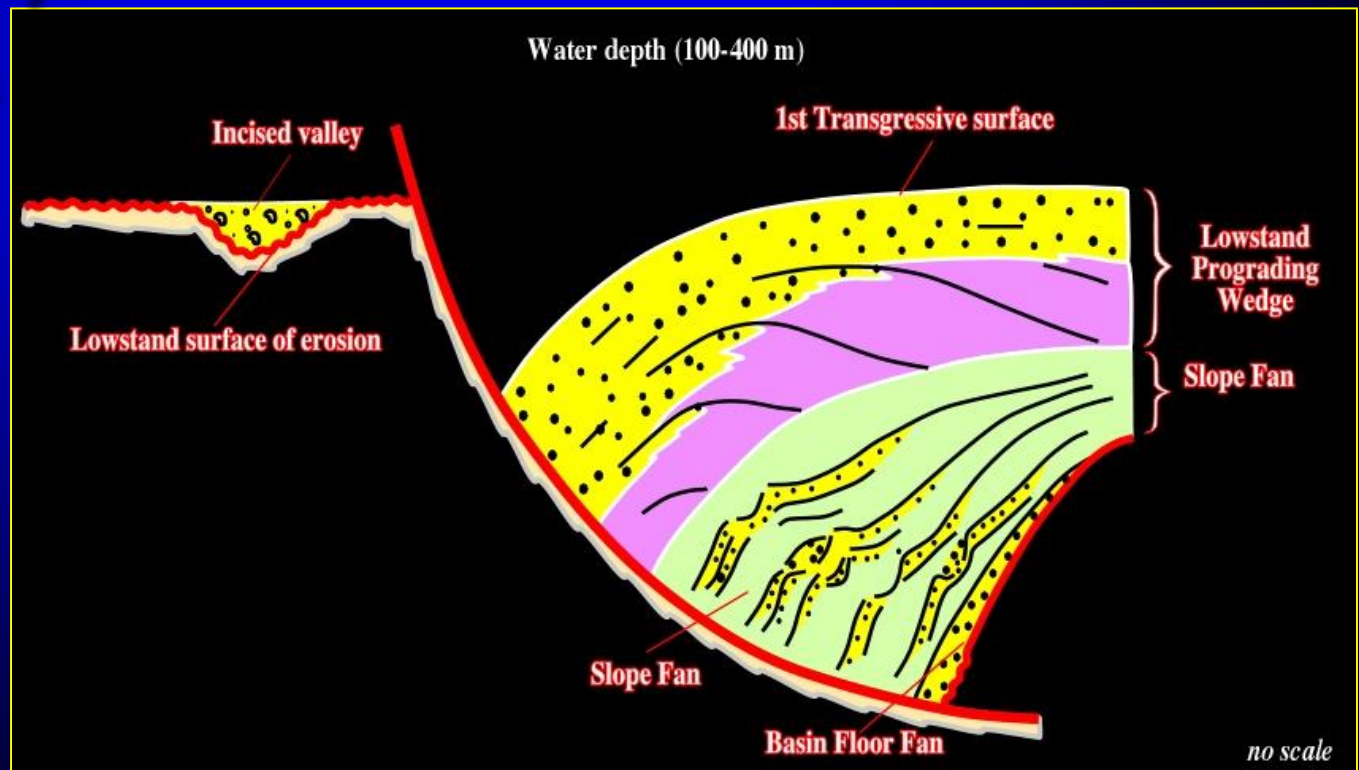
Lowstand System Tract LST

Principle 4

System Tracts

Low Stand System Tract LST

3-Growth-fault setting



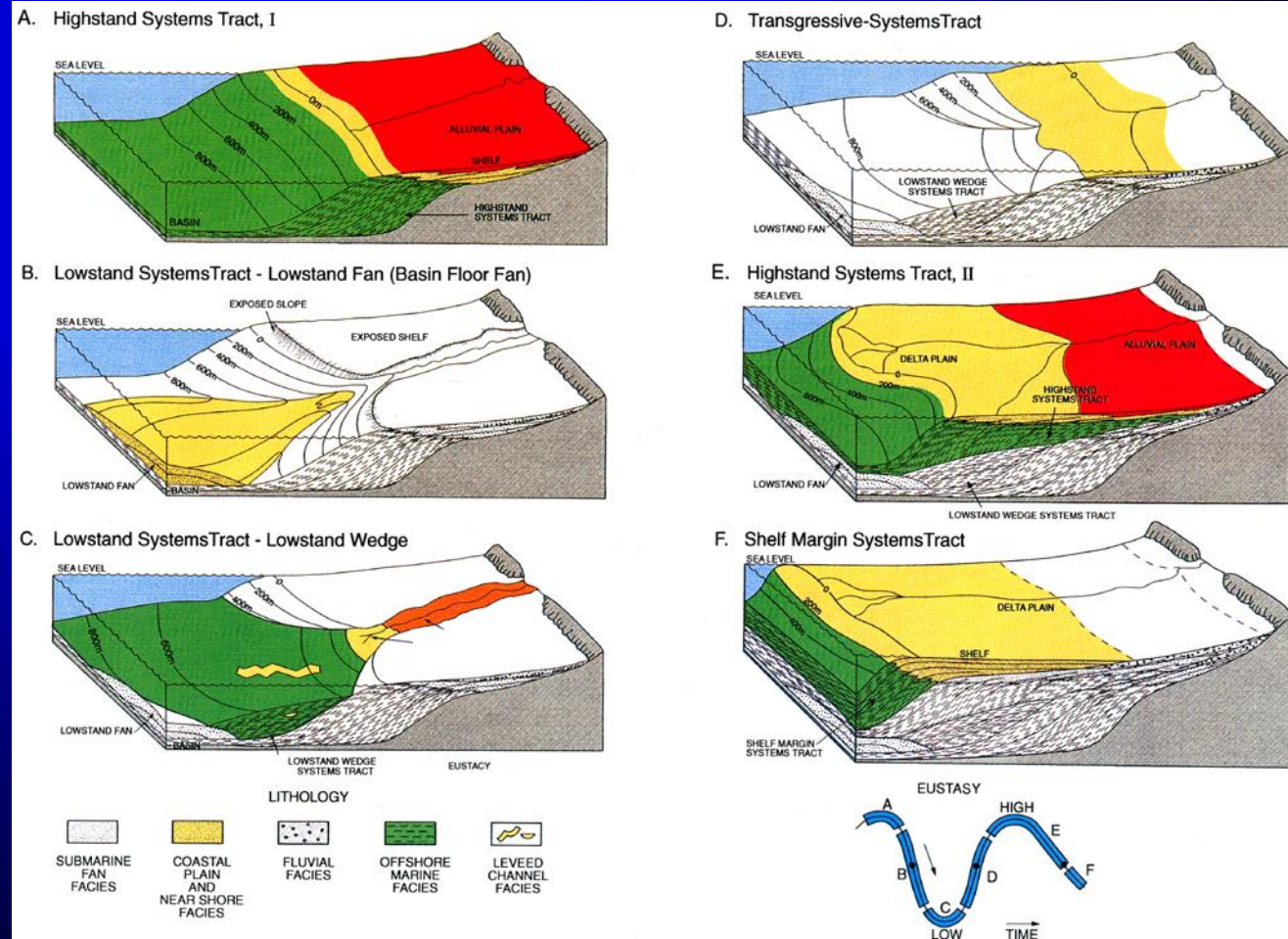
Seismic Sequence Stratigraphy

Principle 4 System Tracts

Lowstand system tract

Transgressive system tract

Highstand system tract

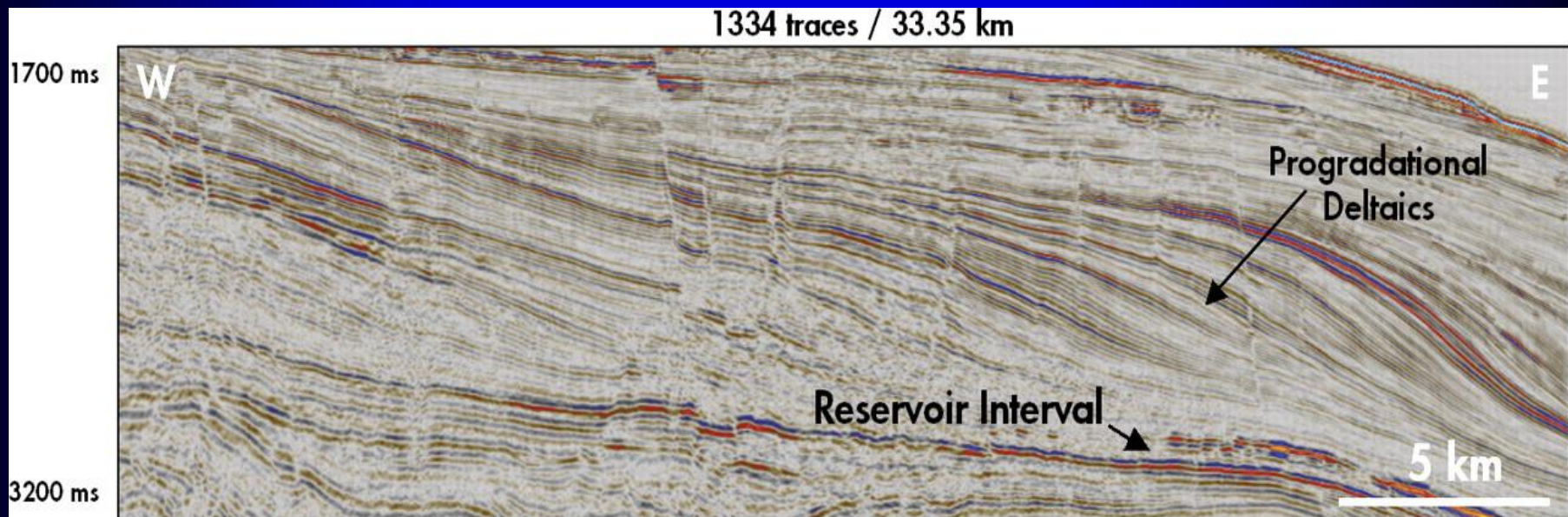


Seismic Sequence Stratigraphy

Principle 4

System Tracts

Define ST

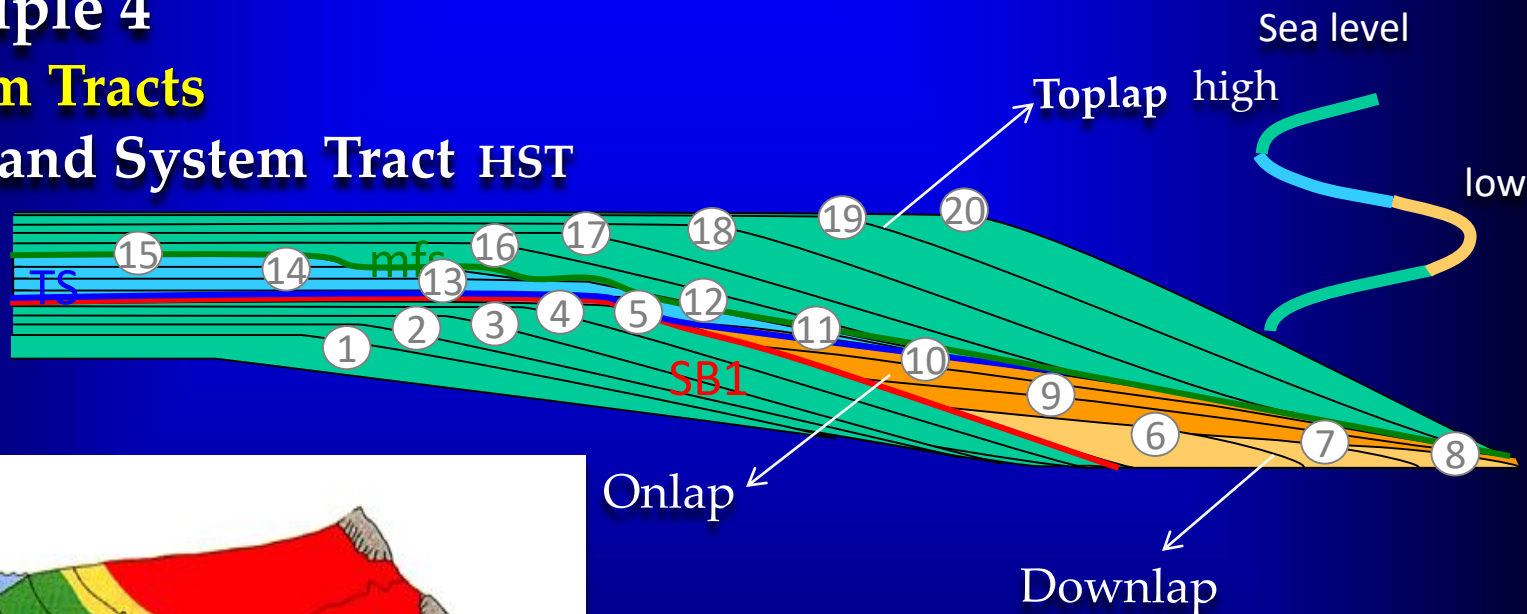


Seismic Sequence Stratigraphy

Principle 4

System Tracts

High Stand System Tract HST

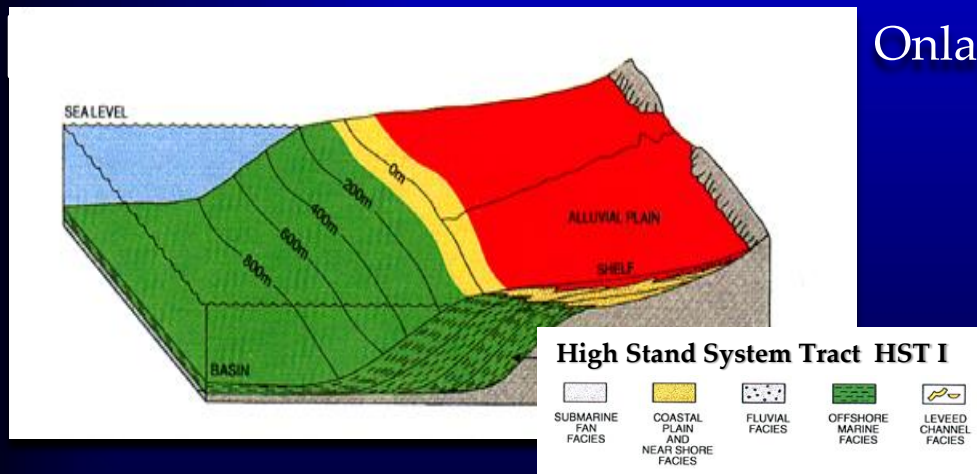


Onlap

Downlap

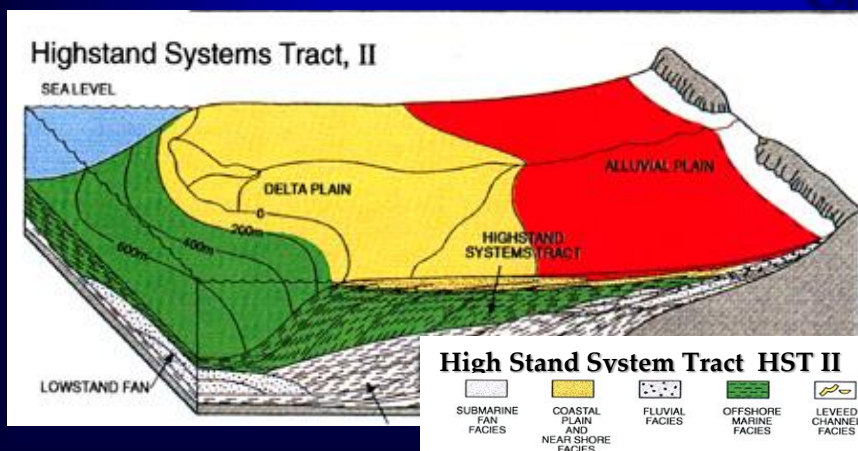
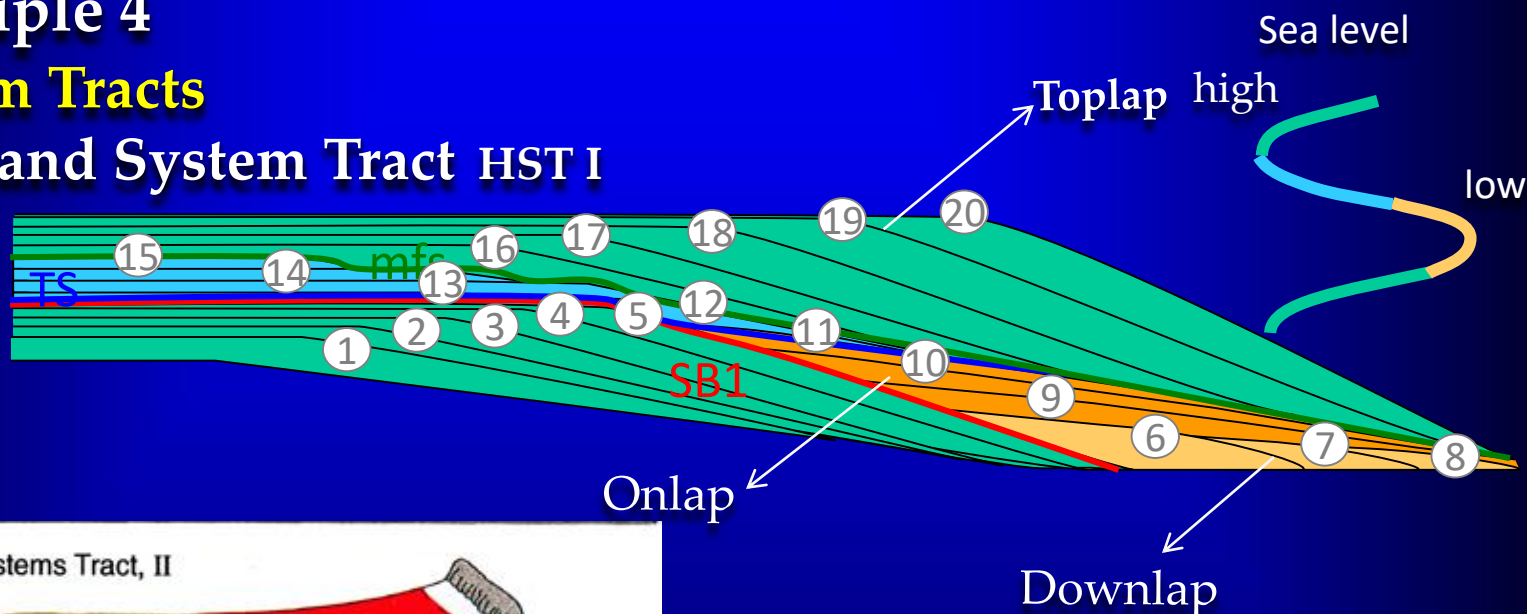
HST

Sea Level stillstand & Low sedimentation Produce Prograding Onlapping and aggrading clinoforms.



Seismic Sequence Stratigraphy

Principle 4 System Tracts High Stand System Tract HST I



HST II

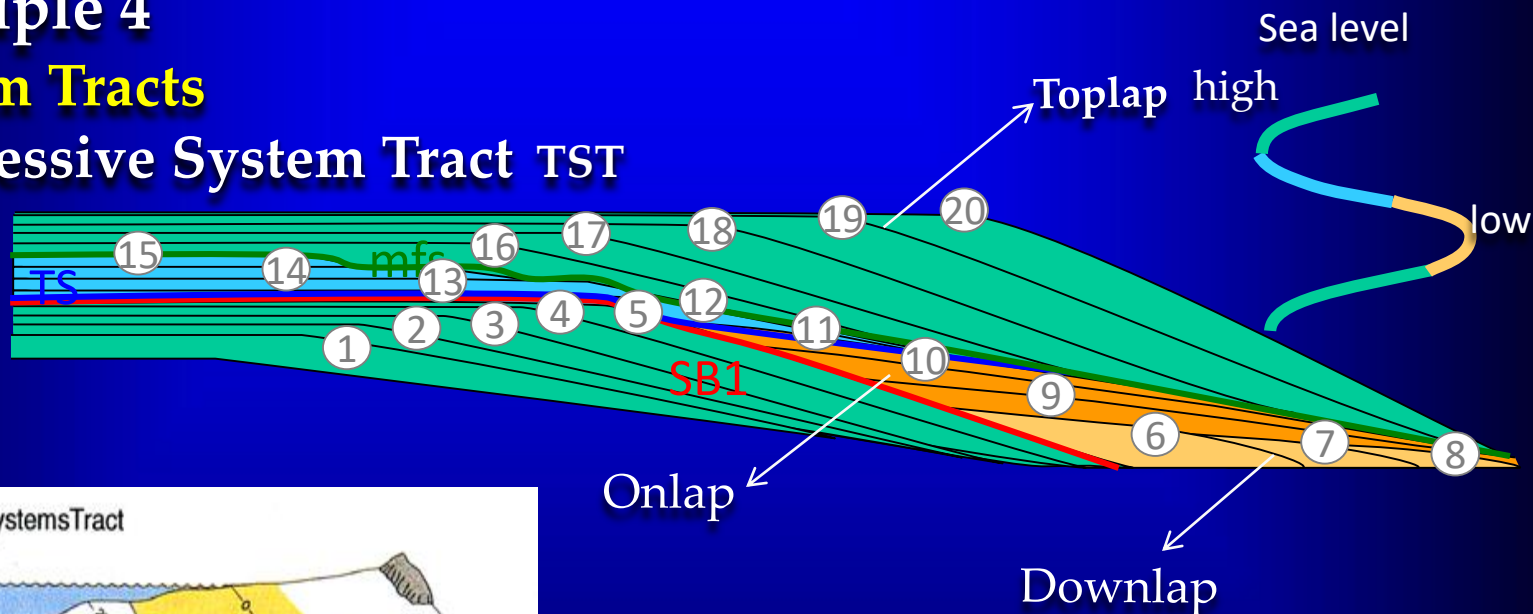
Sea Level stillstand & Low sedimentation
Produce Prograding Onlapping and
aggrading clinoforms.
Lower & Upper margins are sequence
boundaries.

Seismic Sequence Stratigraphy

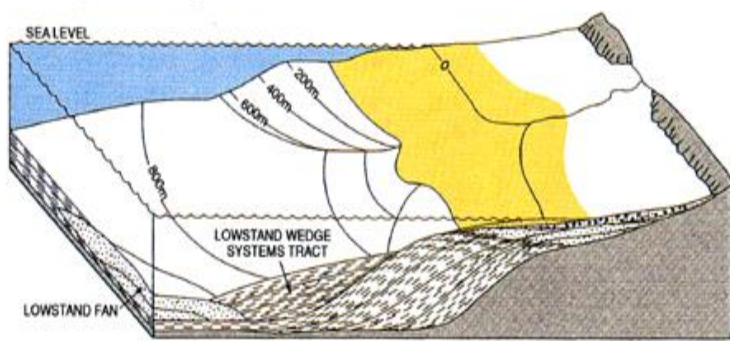
Principle 4

System Tracts

Transgressive System Tract TST



D. Transgressive-SystemsTract



TST

Rapid sea level rise & low sedimentation
Produce Retrogradational onlapping clinoforms.

Seismic Sequence Stratigraphy

Principle 4

System Tracts

Transgressive System Tract TST

- Product of rise in base level (sea level?).
- Lies at boundary between underlying Late Lowstand System Tract and the overlying Transgressive system tract (TST).
- Marine-flooding surface that forms first significant flooding surface in a sequence - often marking base of most prominent onlap.
- Formed when rate of creation of accommodation space is greater than the rate of sediment supply.
- In rimmed carbonate platforms, the rate of sediment supply may keep pace with the rate of relative sea-level rise and thus TS marks change from a progradational to an aggradational parasequence stacking patterns.

Seismic Sequence Stratigraphy

Principle 4

System Tracts

Transgressive System Tract TST

- a) Sands are reworked and well sorted by coastal processes. Reservoir quality sands vary from good to poor, depending upon grain size and cementation and tend to be parallel to the ancient coastline.
- b) The continuity of transgressive sands is typically good along depositional strike, but may vary in the depositional dip direction.
- c) The backstepping nature of transgressive deposits tends to produce interbedded sands and shales in a terrigenous clastic environment and packstones and mudstones in a carbonate environment. Multiple pay reservoirs may result. Reservoir units are interbedded with potential hydrocarbon source units.

Seismic Sequence Stratigraphy

Principle 4

System Tracts

Transgressive System Tract TST

- d) Because of their degree of interbedding and their onlapping nature updip pinchouts may also produce stratigraphic entrapment of transgressive reservoir sands.
- e) Transgressive systems tract sediments tend to be overlain by a continuous shale seal that may also be a hydrocarbon source, i.e., the condensed section.
- f) If high sediment discharge rates coincide with moderate rates of marine onlap, then braided stream deposits may cover all or portions of the exposed shelf during lowstand and early transgressive systems tracts time. This can provide an excellent sheet reservoir sand.

Seismic Sequence Stratigraphy

Principle 4

System Tracts

Transgressive System Tract TST

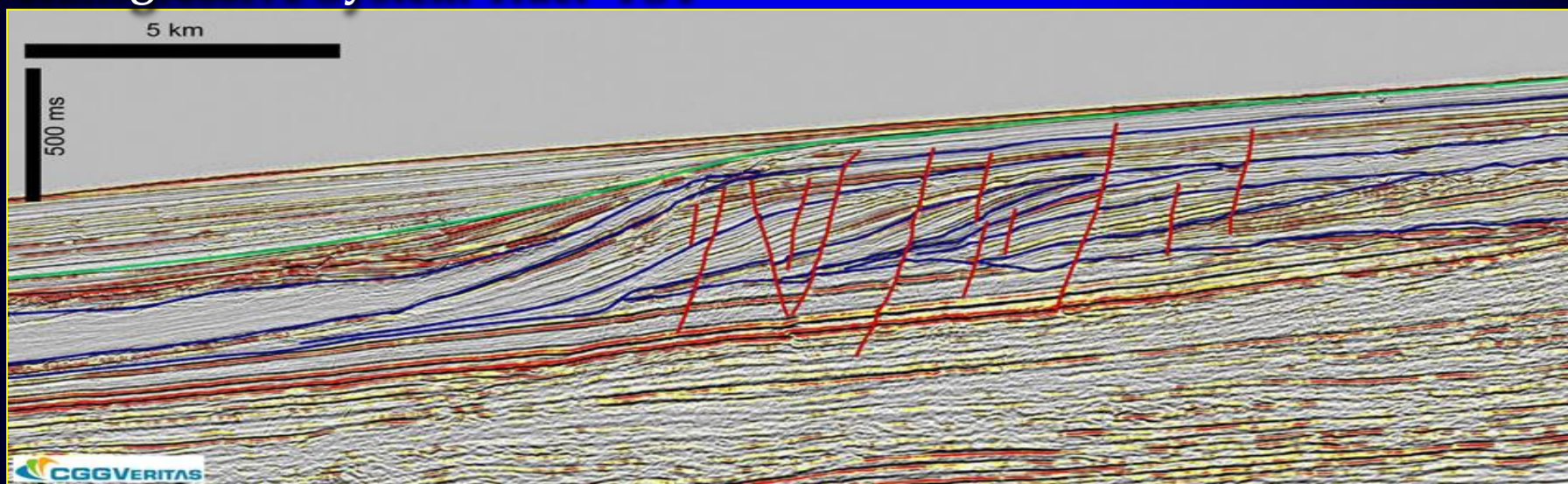
g) If marine onlap extends high on the shelf and thereby encroaches the area where alluvial fan deposits formed during late highstand time, the alluvial gravels may be reworked by coastal processes. The resulting coarse clastic sands are of reservoir quality because they are winnowed clean of their fine fraction by wave and current action.

Seismic Sequence Stratigraphy

Principle 4

System Tracts

Transgressive System Tract TST



The stratal geometries on the shelf show progradational and aggradational geometry together with subtle slump scars. In 3D these mega forms probably trace lobes - hence the complex lap relationships. The stratal surfaces in the clinoforms (picked in blue) are cut by an array of moderately-dipping (once the excessive vertical exaggeration is removed) normal faults that do not continue to depth. These probably represent incipient failure of the stratal package upon a muddy section. These faults - which involve c. 6-700 ms (= c. 1 km) of strata may also influence the failure on the foresets. Author: [Rob Butler](#)

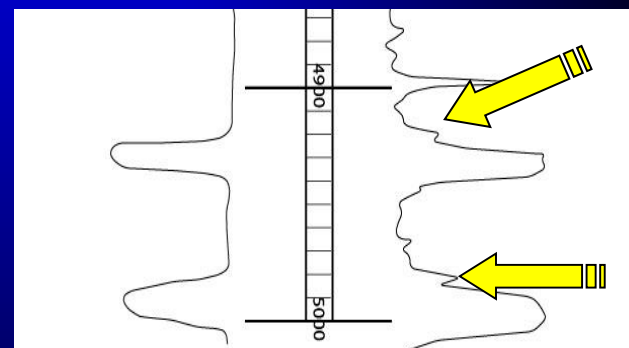
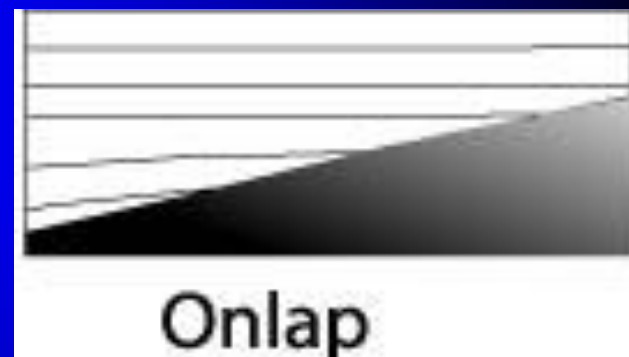
Seismic Sequence Stratigraphy

Principle 4

System Tracts

Transgressive System Tract TST

- Defined by erosion or incision of underlying onlapped sediment (Ravinement).
- Inferred from presence of Glossifungites in this surface.
- Inferred from presence of nick or neck on resistivity logs caused by presence of carbonate cements probably derived from the carbonate fauna eroded during the Ravinement



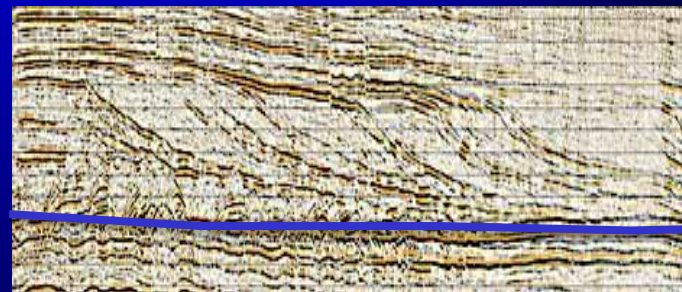
Seismic Sequence Stratigraphy

Principle 4

System Tracts

Maximum Flooding system MSF

- The maximum flooding surface caps the transgressive systems tract and marks the turnaround from retrogradational stacking in the transgressive systems tract to aggradational or progradational stacking in the early highstand systems tract.
- The maximum flooding surface represents the last of the significant flooding surfaces found in the transgressive systems tract and is commonly characterized by extensive condensation and the most landward extent of the marine condensed facies.



- Defined as lying immediately below the downlapping reflectors prograding reflectors of the HST

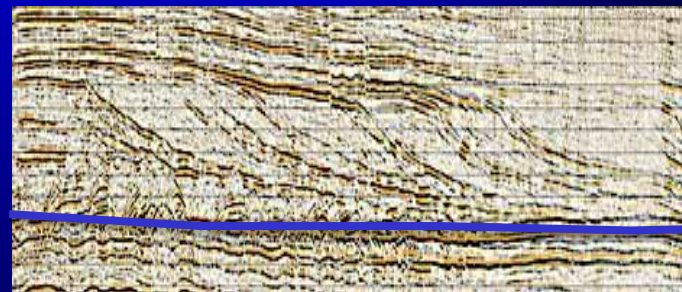
Seismic Sequence Stratigraphy

Principle 4

System Tracts

Maximum Flooding system MSF

- Product of maximum flooding or transgression of shelf or stillstand in base level (sea level?)
- Lies at the boundary between the underlying Transgressive system tract (TST) and the overlying High stand system tract (HST)
- Often expressed as a downlap surface.
- Marine shelf and basinal sediments associated with this surface product of slow rates of deposition of pelagic-hemipelagic sediments
- Make up condensed section and are usually thin



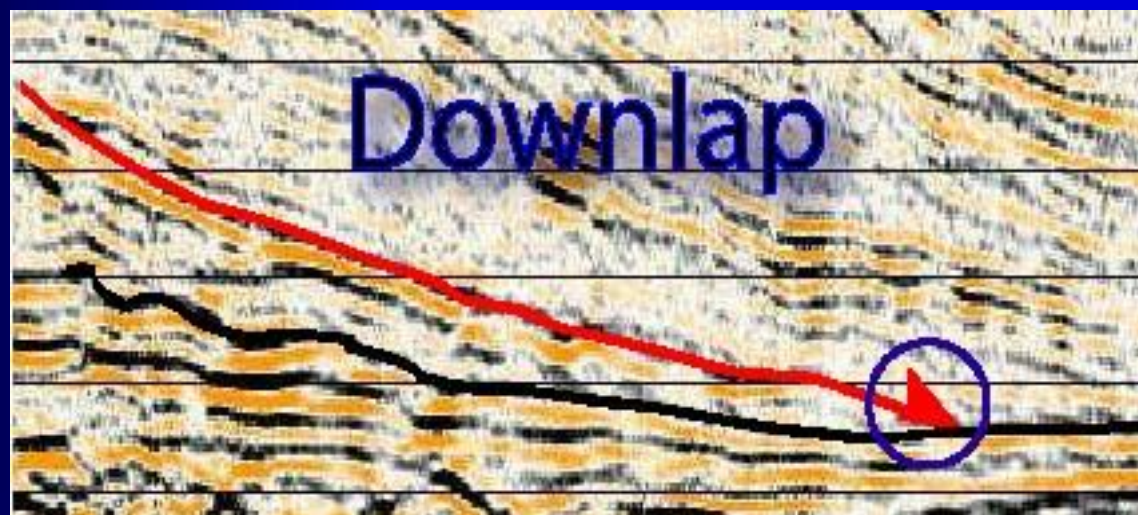
- Defined as lying immediately below the downlapping reflectors prograding reflectors of the HST

Seismic Sequence Stratigraphy

Characteristics of System Tracts from seismic, well logs, core & outcrop

Maximum Flooding Surface MFS

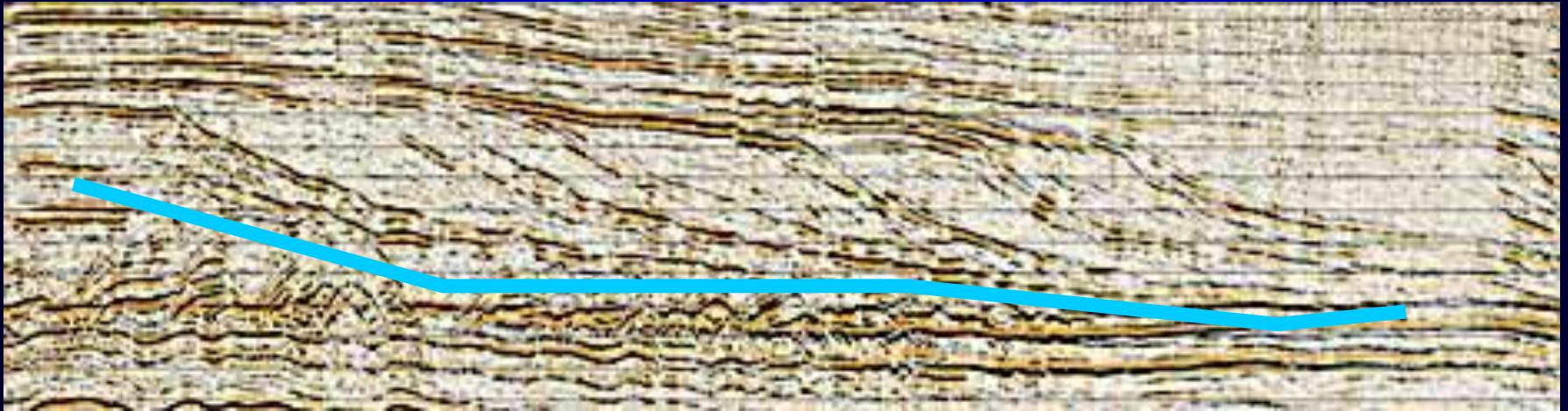
- Often expressed as a downlap surface.



Seismic Sequence Stratigraphy

Characteristics of System Tracts from well logs, core & outcrop
Maximum Flooding Surface MFS

- Defined as lying immediately below the downlapping reflectors prograding reflectors of the HST

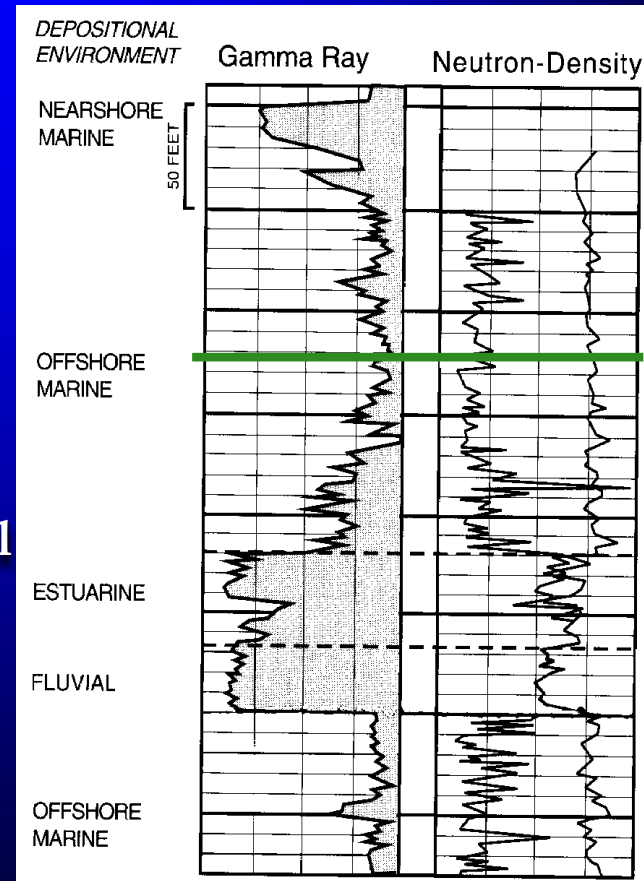


Seismic Sequence Stratigraphy

Characteristics of System Tracts from seismic, well logs, core & outcrop

Maximum Flooding Surface MFS

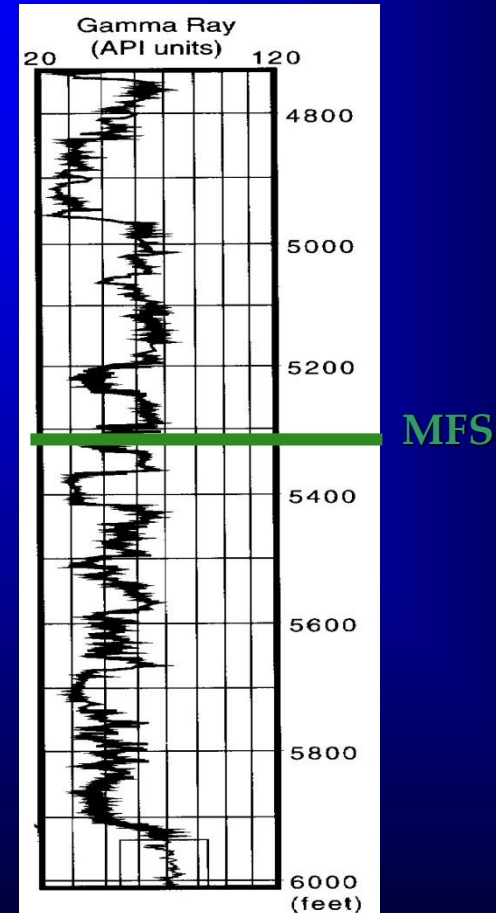
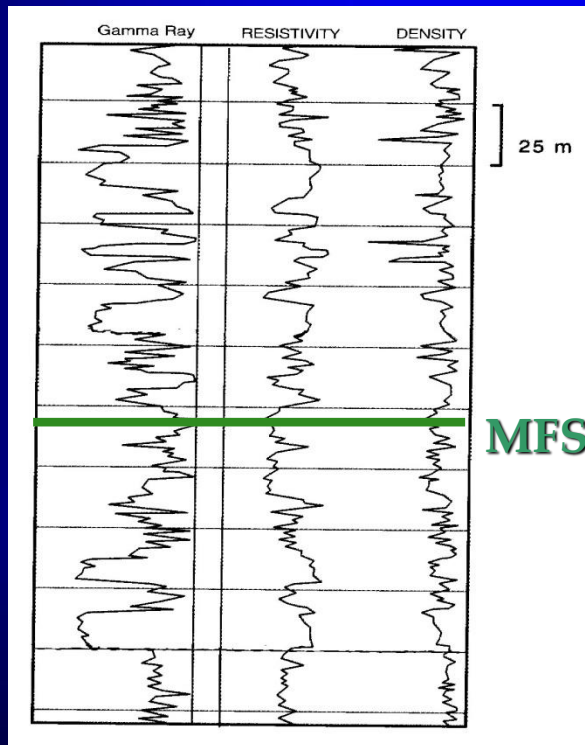
- Defined by organic often radioactive (big kicks on gamma ray logs) black shales.
- Not infrequently overlain by coarser sediments (often sand sized).
- Inferred from presence of condensed faunal association.
- Inferred from presence of finest grain size



Seismic Sequence Stratigraphy

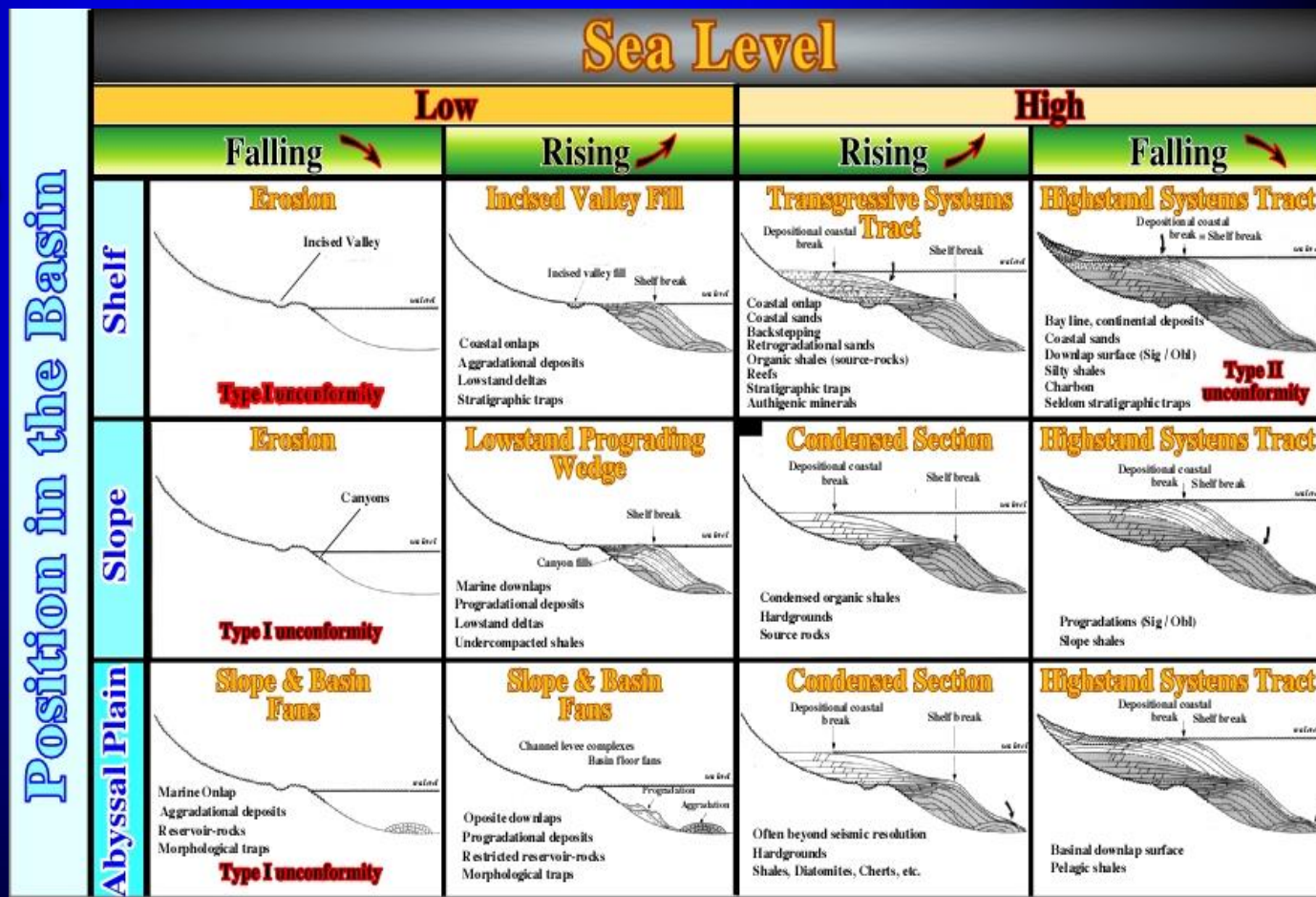
Characteristics of System Tracts from seismic, well logs, core & outcrop

Maximum Flooding Surface MFS



Seismic Sequence Stratigraphy

Principle 5 Sea level & System Tracts



Seismic Sequence Stratigraphy

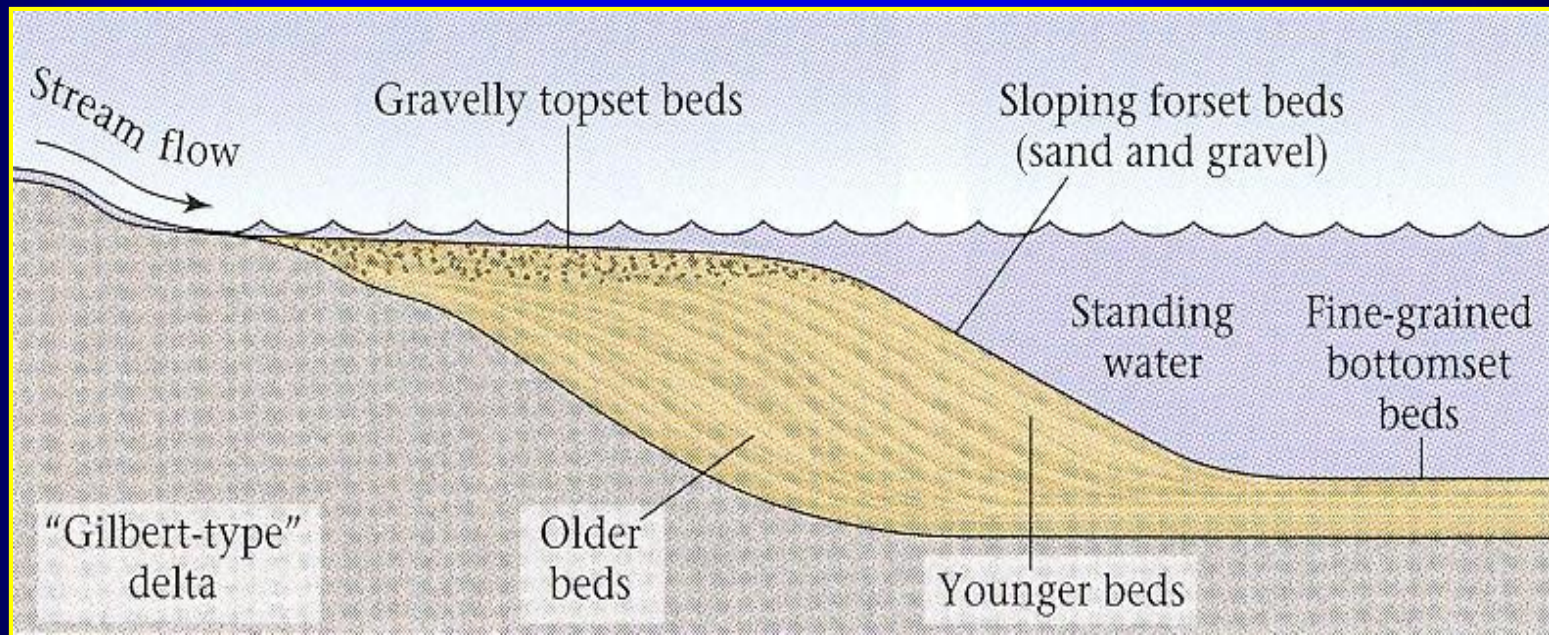
Principle 5 Sea level & System Tracts



Seismic Sequence Stratigraphy

Principle 3

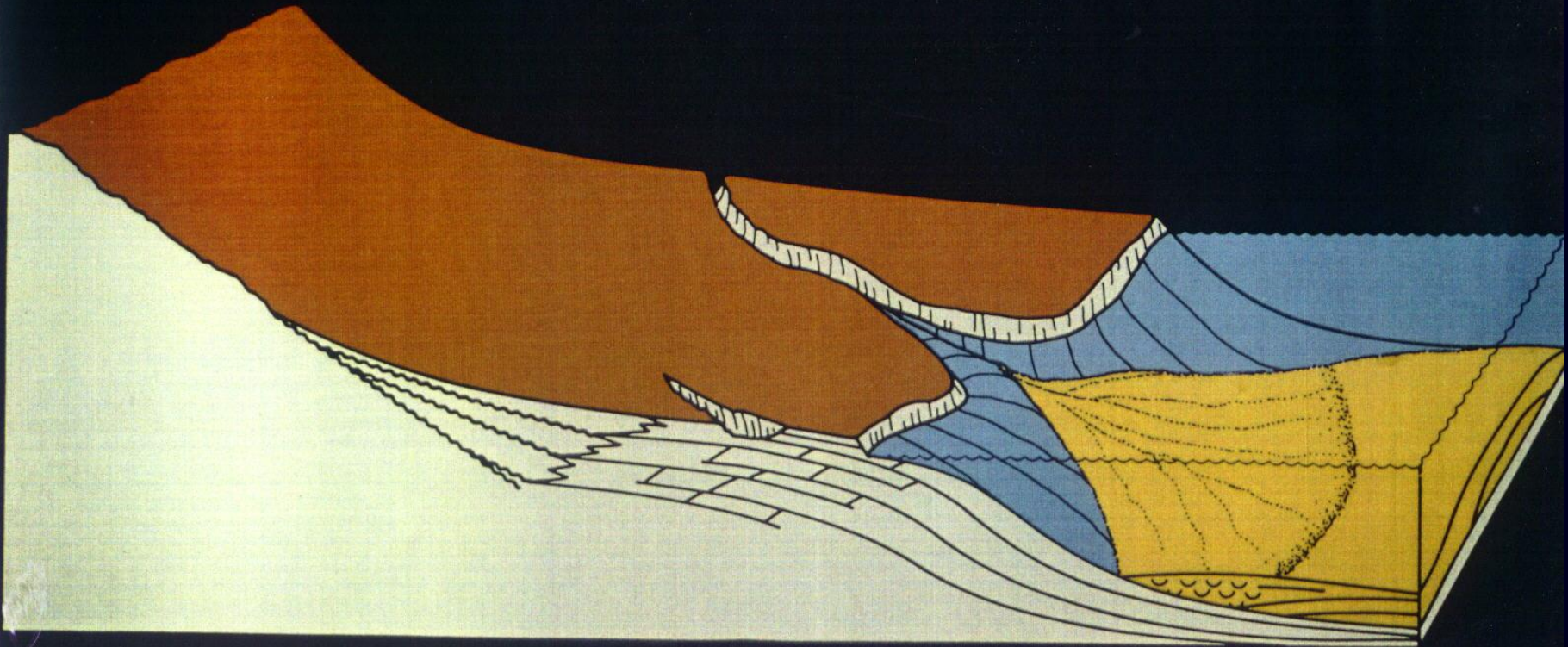
Sequence Definition Clinoforms



2. Depositional system interpretation

2.3 systems tract interpretation

LOWSTAND WEDGE SYSTEMS TRACT LOWSTAND FAN



MIOCENE LOWSTAND DEPOSITS SAN JOAQUIN BASIN, CA.

W

E

3.0

3.5

4.0

4.5

SECONDS

INCISED
VALLEY

PROGRADING
LOWSTAND
WEDGE

LOWSTAND
FAN

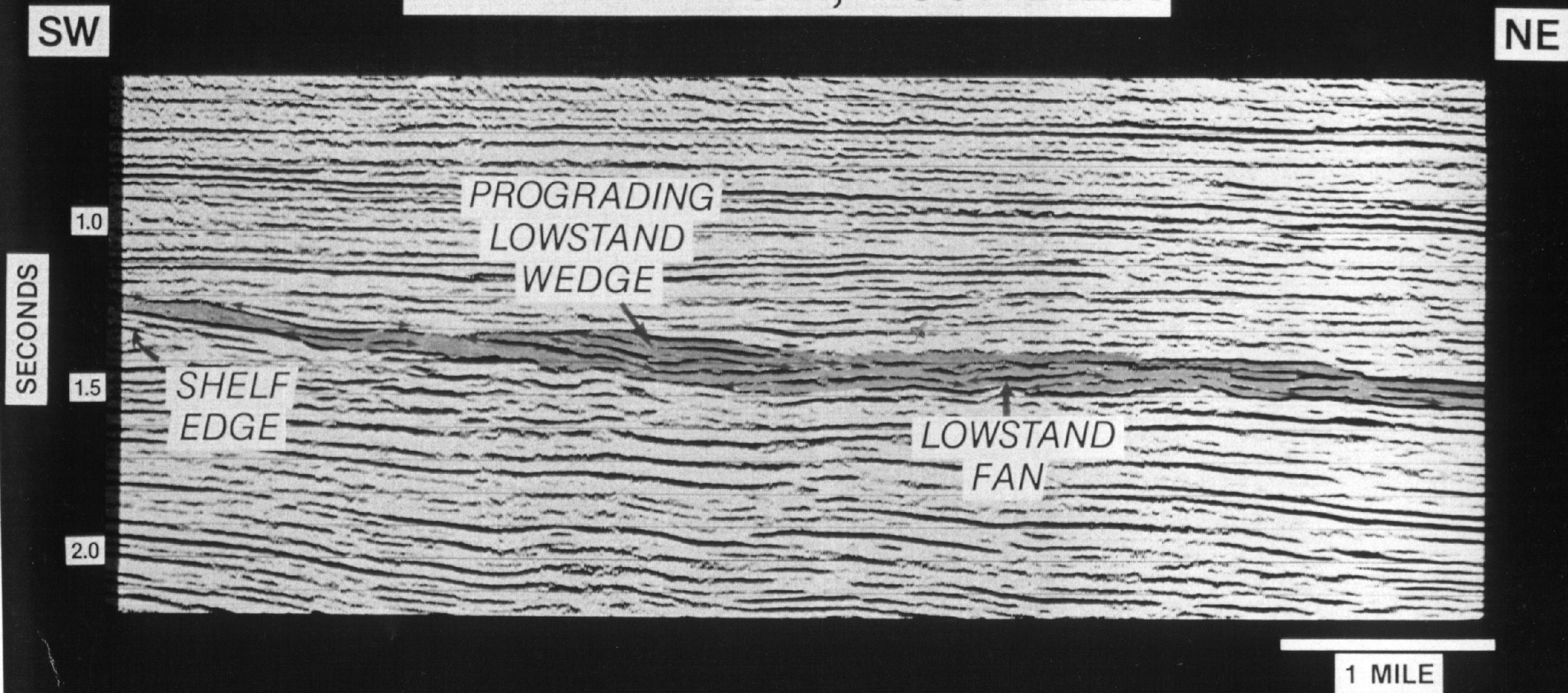
SHELF EDGE

LEGEND

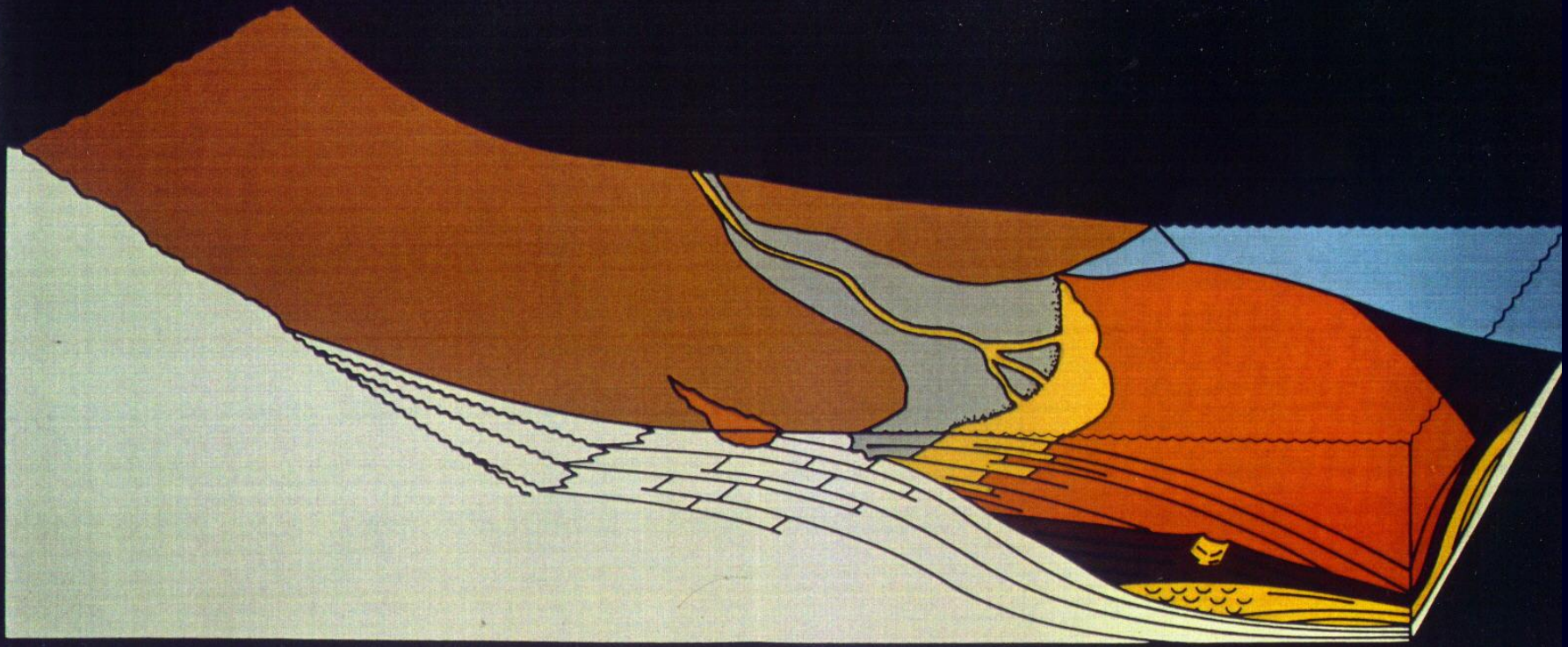
- HIGHESTAND DEPOSITS
- TRANSGRESSIVE DEPOSITS
- LOWSTAND WEDGE, INCISED VALLEY
FILL DEPOSITS
- LOWSTAND FAN DEPOSITS

LOWER JURASSIC LOWSTAND DEPOSITS

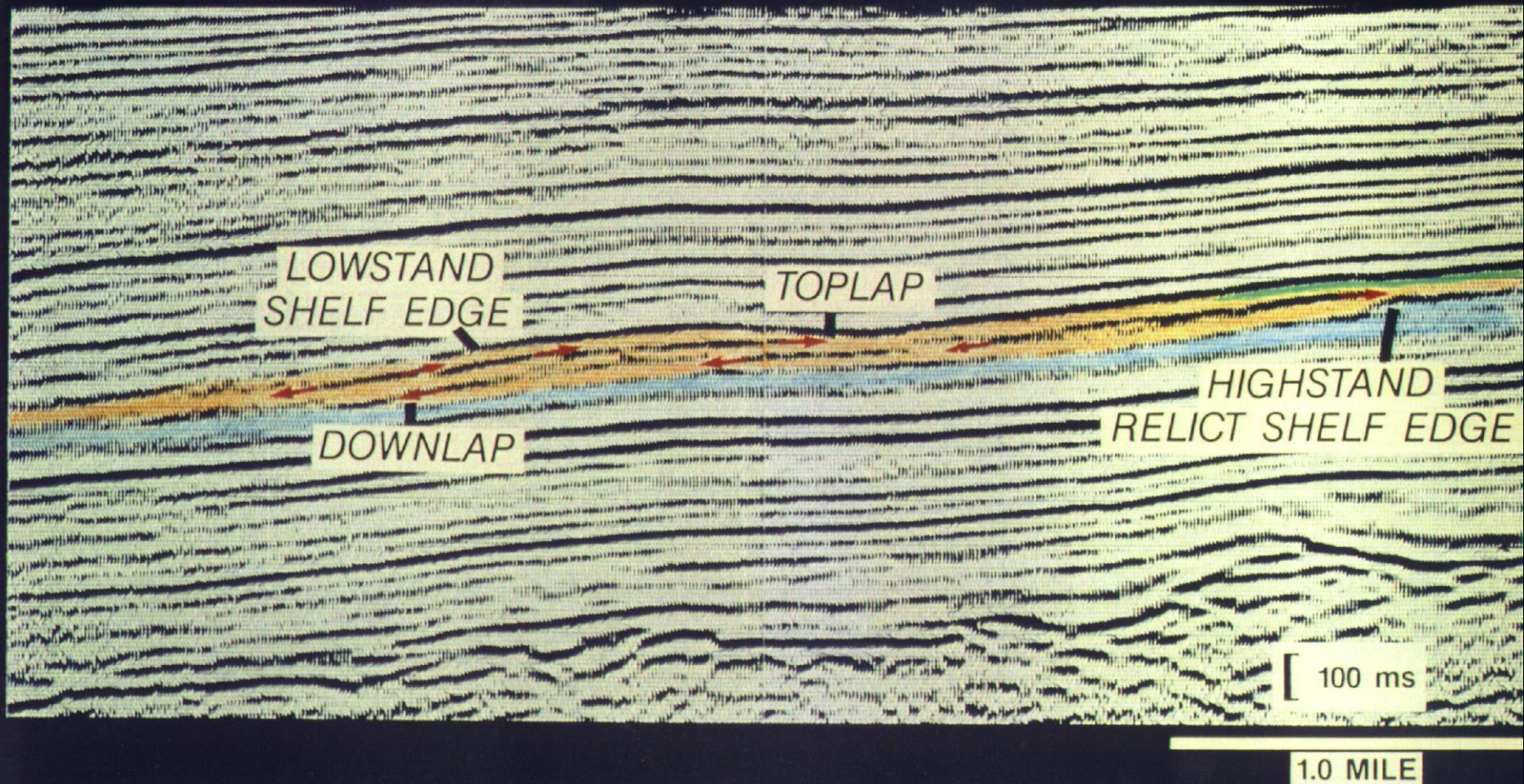
DAMPIER BASIN, AUSTRALIA



LOWSTAND WEDGE SYSTEMS TRACT PROGRADING COMPLEX



MIOCENE SAN JOAQUIN BASIN, CA. PROGRADING LOWSTAND WEDGE



SEISMIC SEQUENCE ANALYSIS CRETACEOUS, NORTH SLOPE, ALASKA

W

TRANSGRESSIVE DEPOSITS

LOWSTAND WEDGE

CANYON

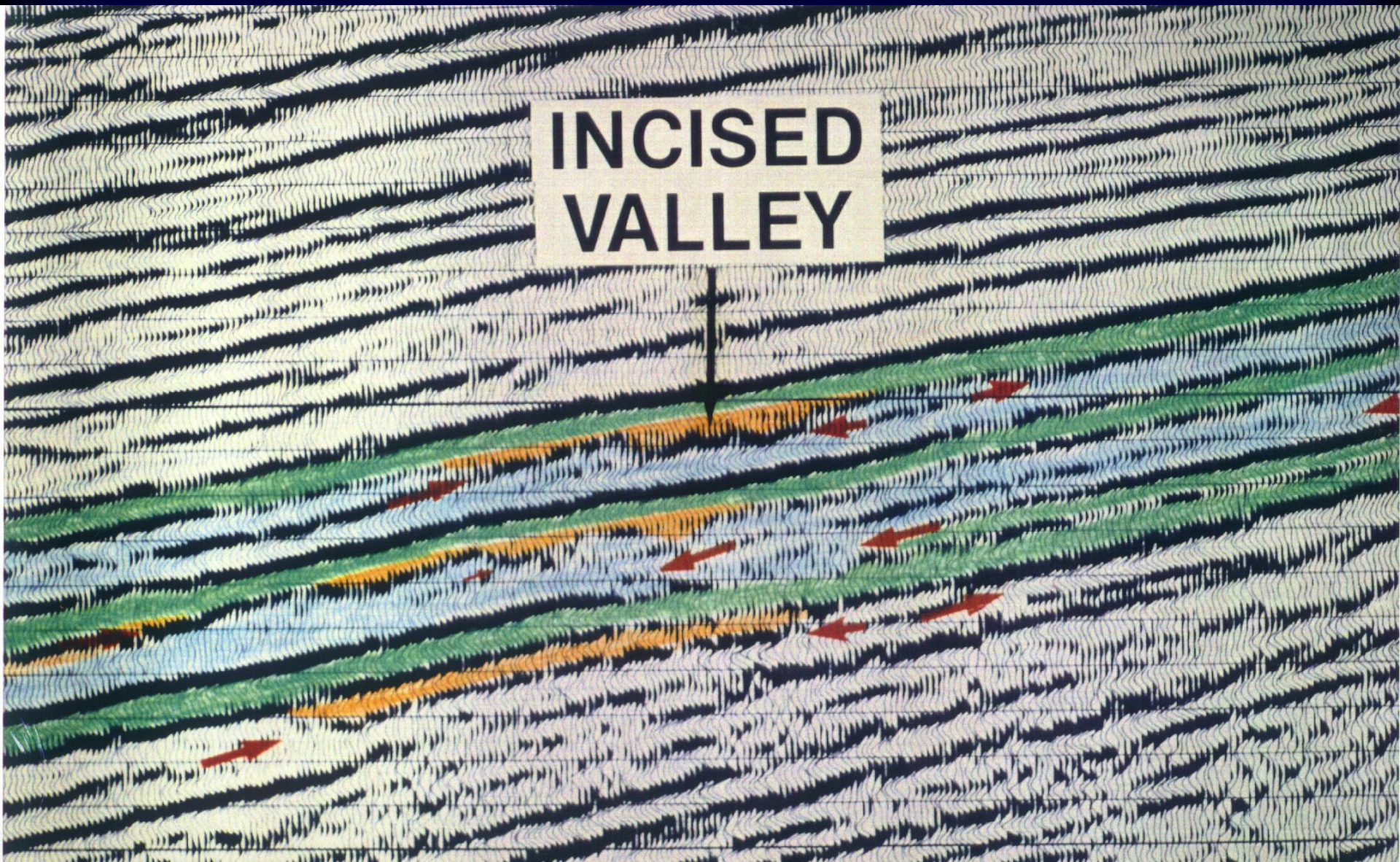
LOWSTAND FAN

LEGEND

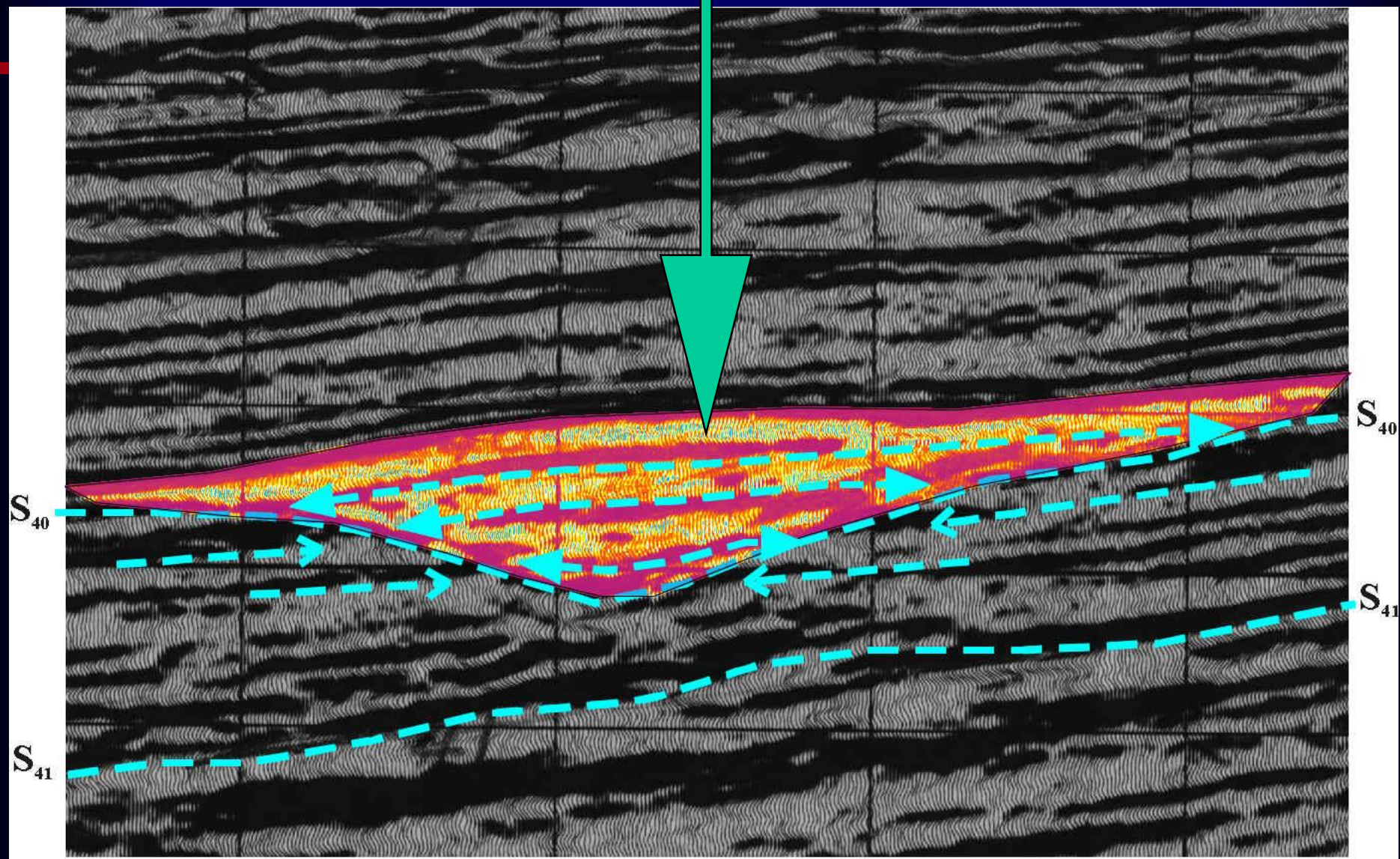
- HIGHSTAND DEPOSITS
- TRANSGRESSIVE DEPOSITS
- LOWSTAND WEDGE
- INCISED VALLEY FILL
- LOWSTAND FAN

1.0 MILE

INCISED VALLEY



下切谷



95G3383线：S30界面上LST的油积扇体

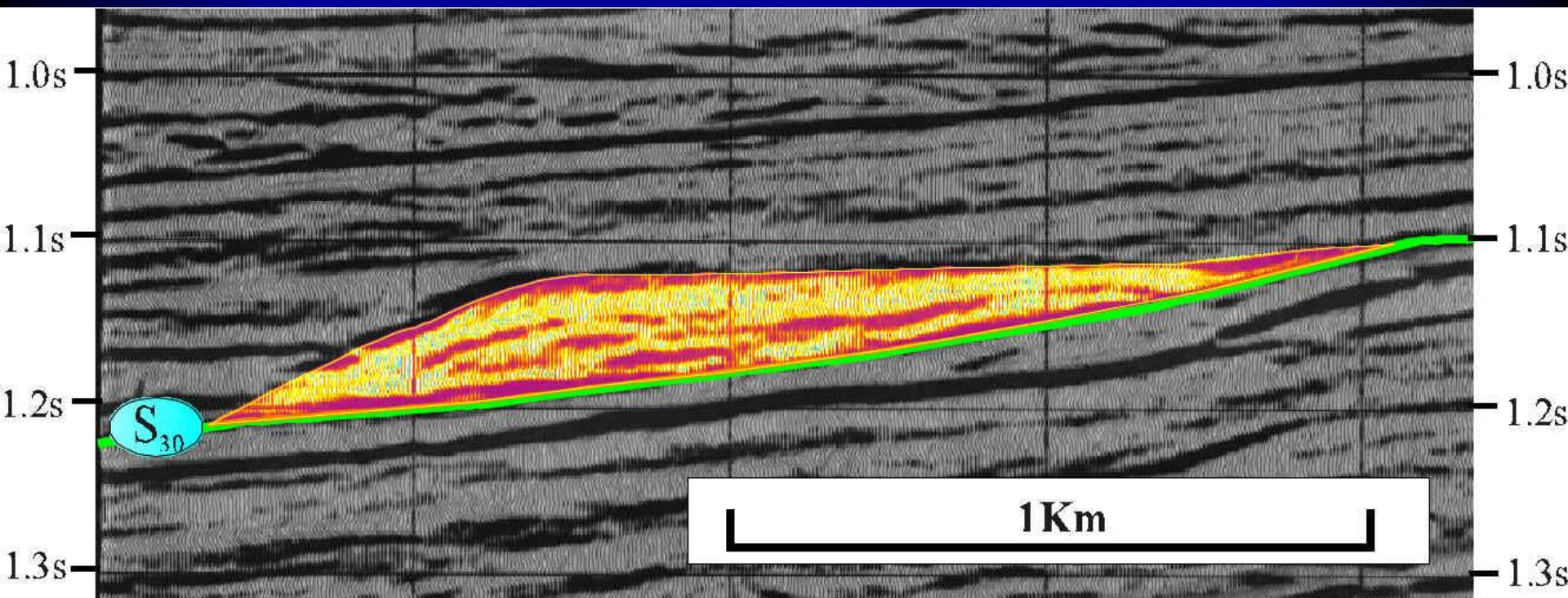


图3-11 95G3383测线上 S_{30} 界面上的低位扇地震相反射特征

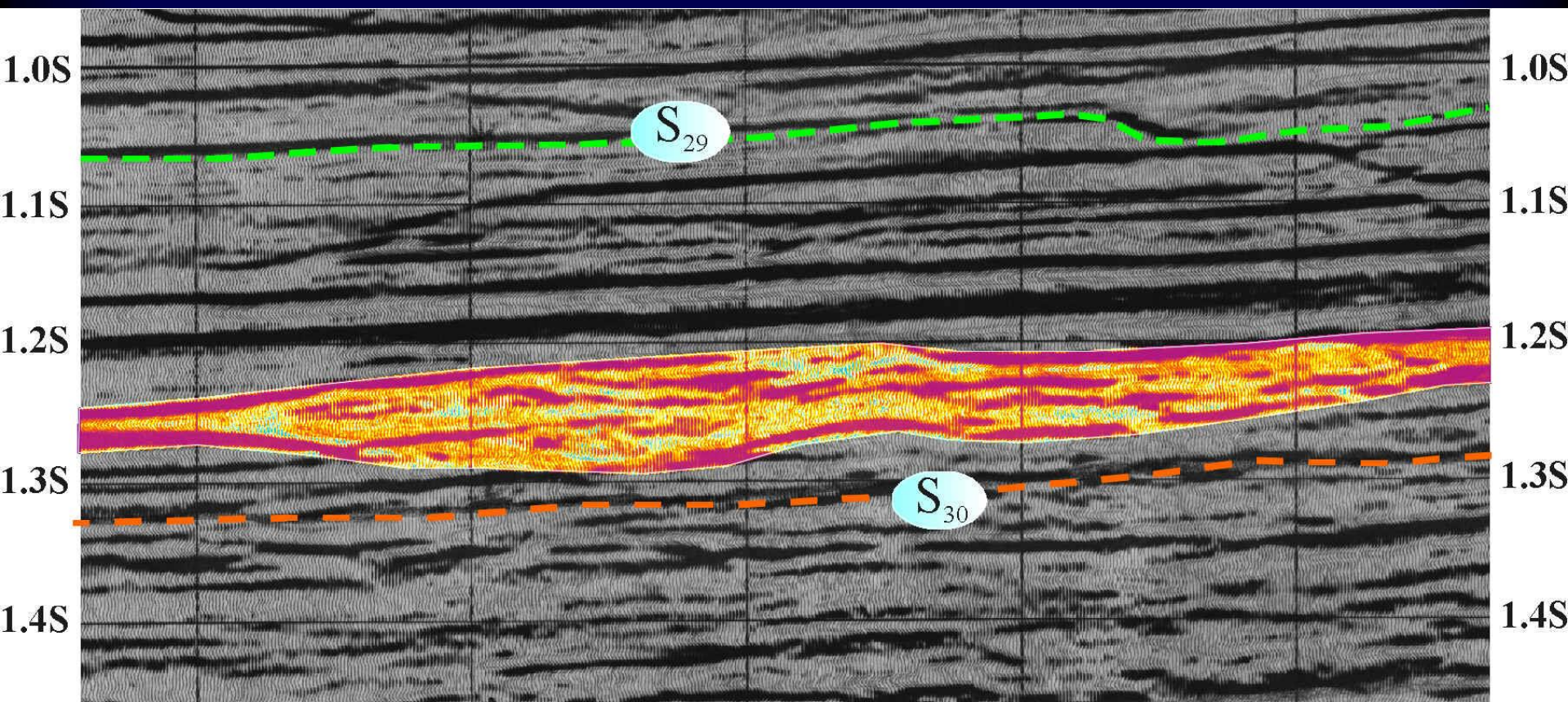


图3-13 莺东斜坡带95G3383测线S₃₀~S₂₉层序低位体系域(LST)水道充填体地震反射特征

913383线: LST:水道充填体

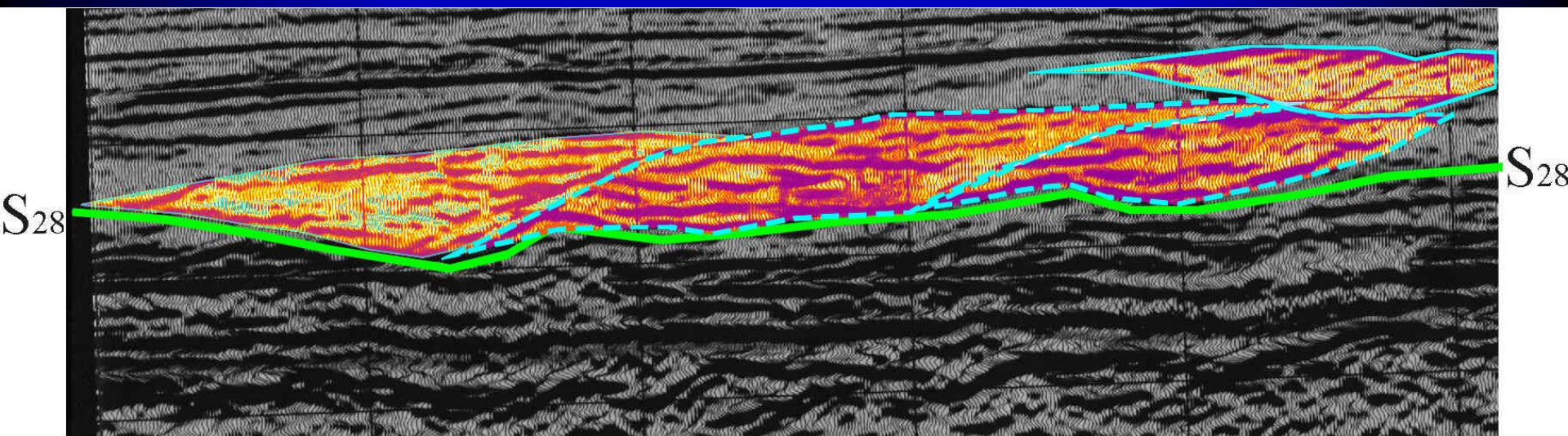
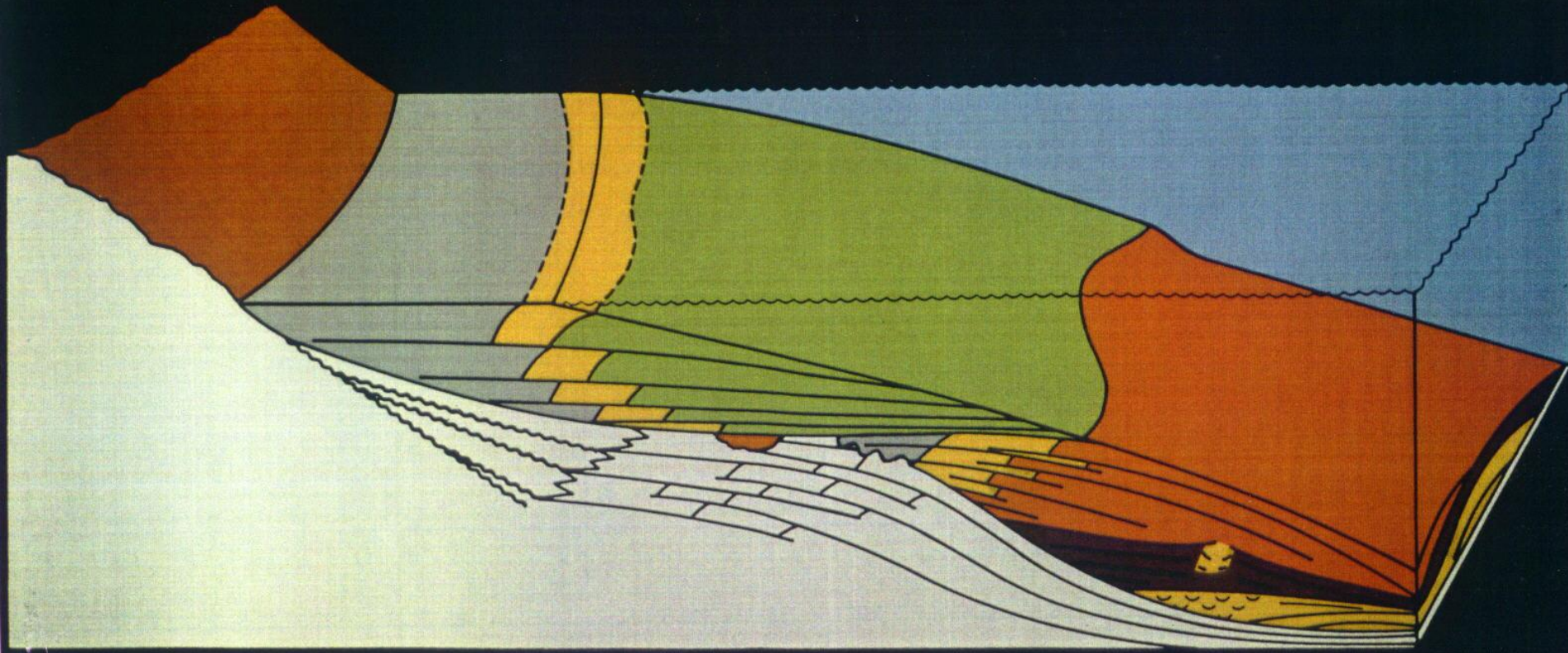


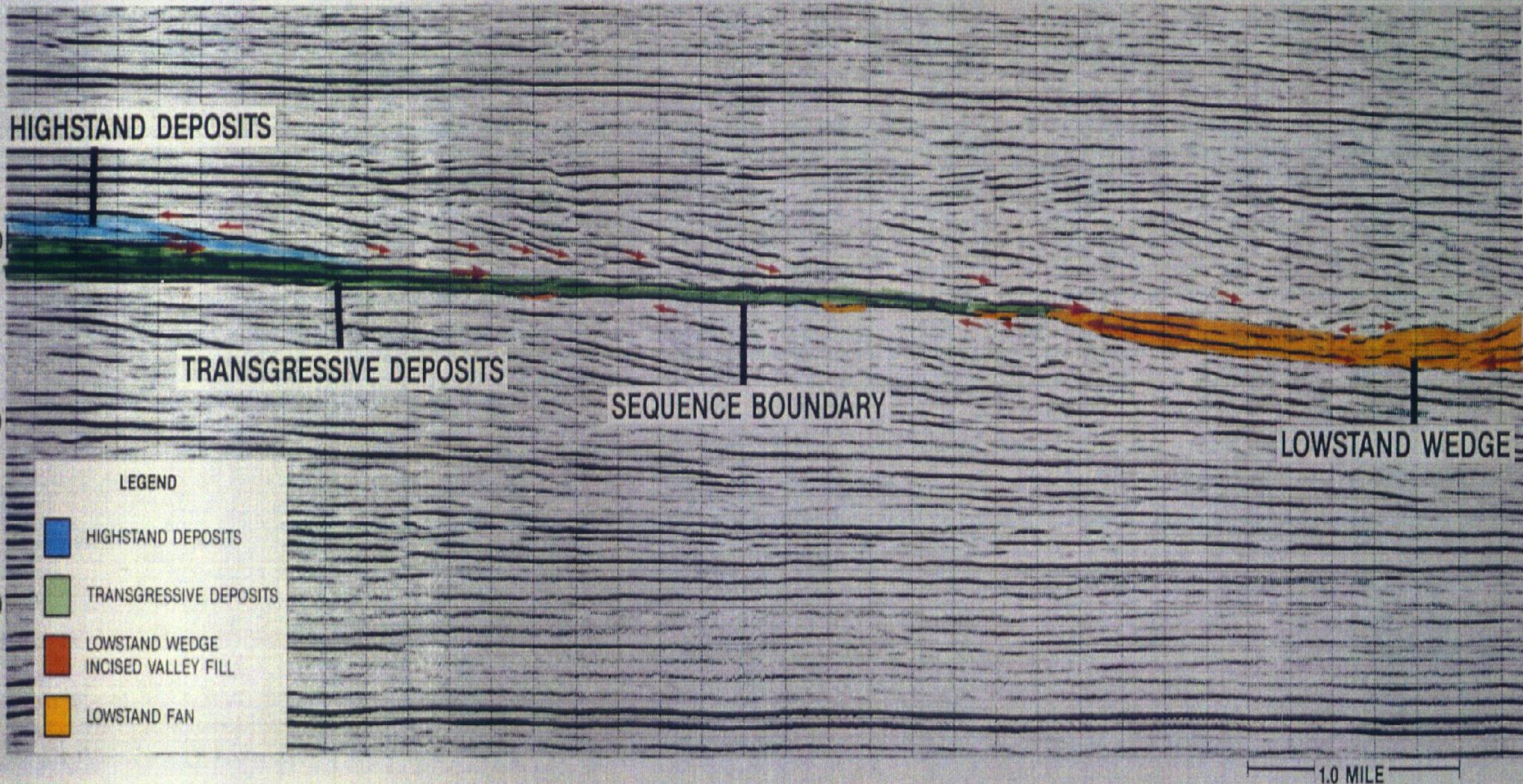
图3-20 94G3425测线S28层序界面之上河道的地震反射特征（VII₁型地震相）

TRANSGRESSIVE SYSTEMS TRACT



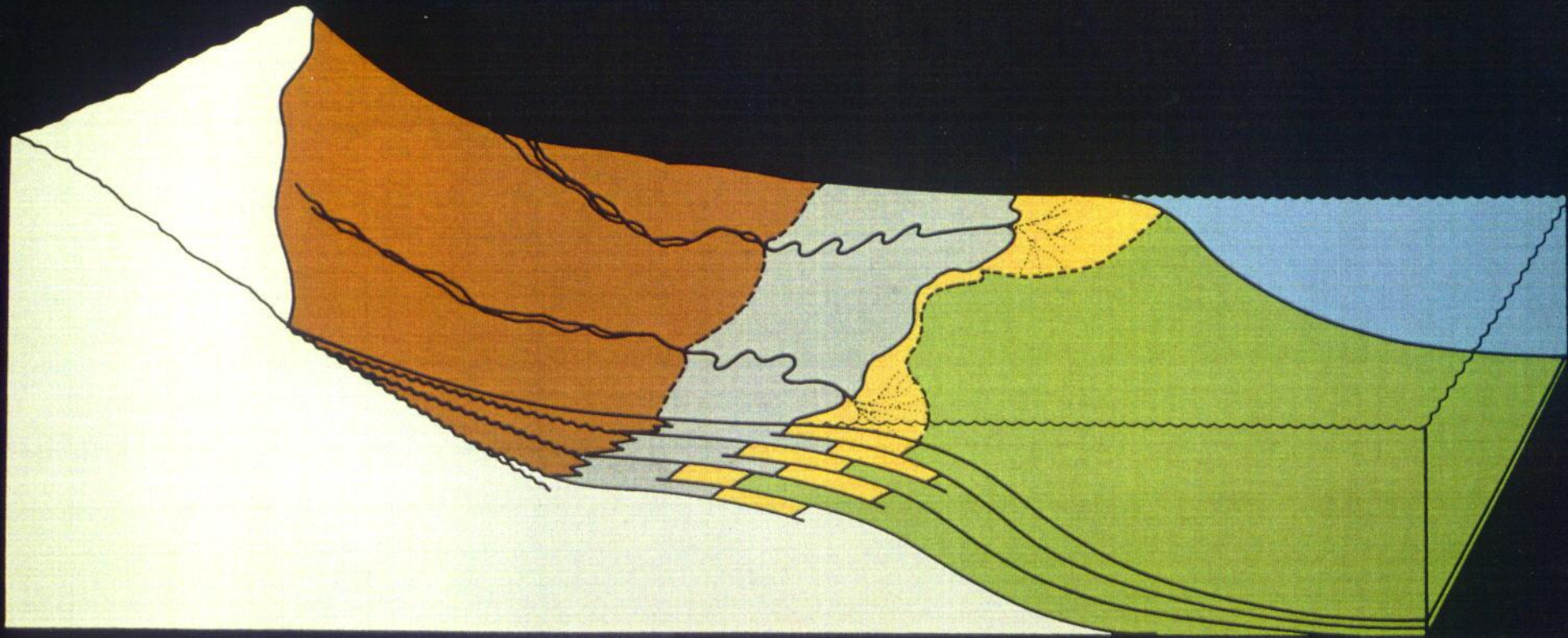
SEISMIC SEQUENCE ANALYSIS MID-CRETACEOUS, ALASKA

W

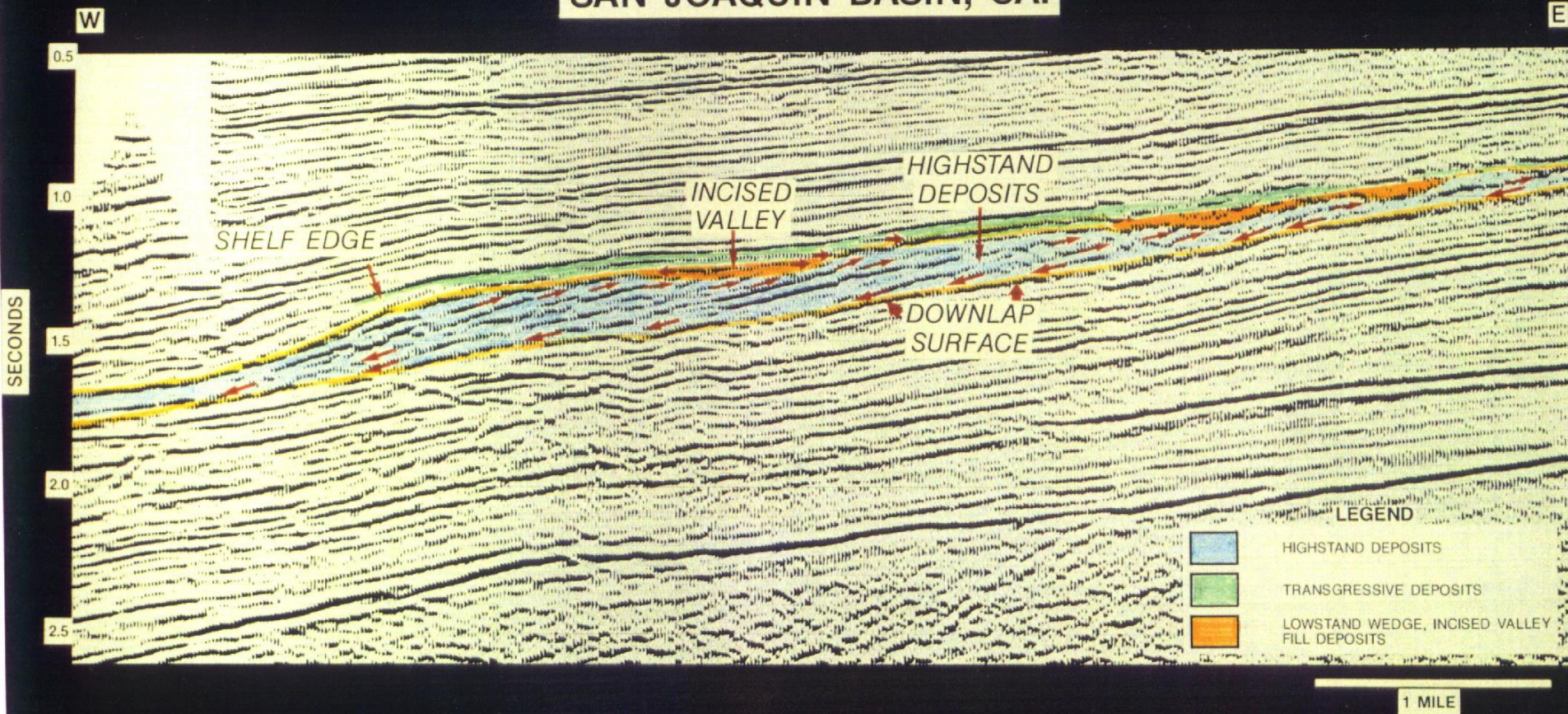


ALI BAKR

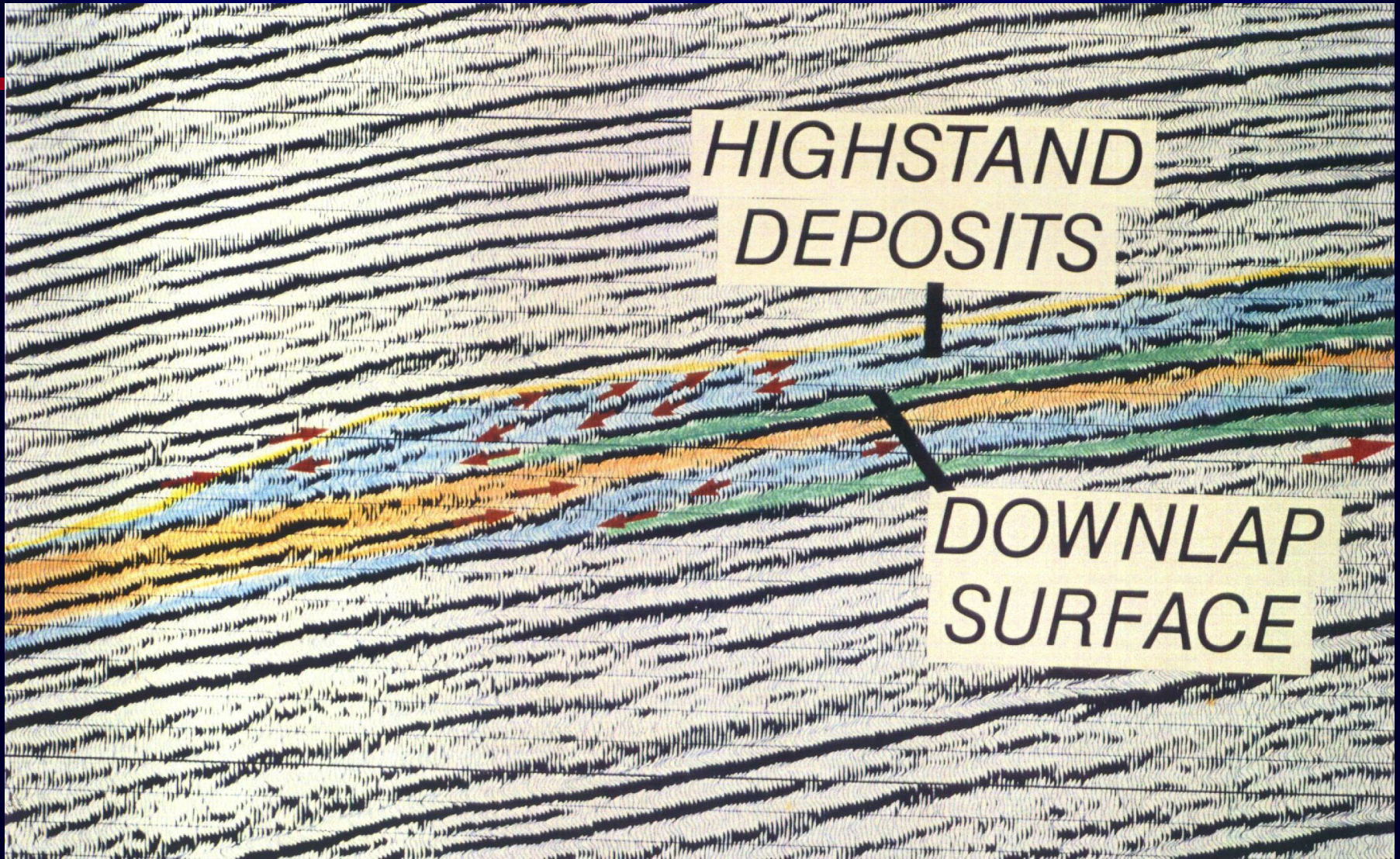
HIGHSTAND SYSTEMS TRACT



UPPER MIOCENE SAN JOAQUIN BASIN, CA.

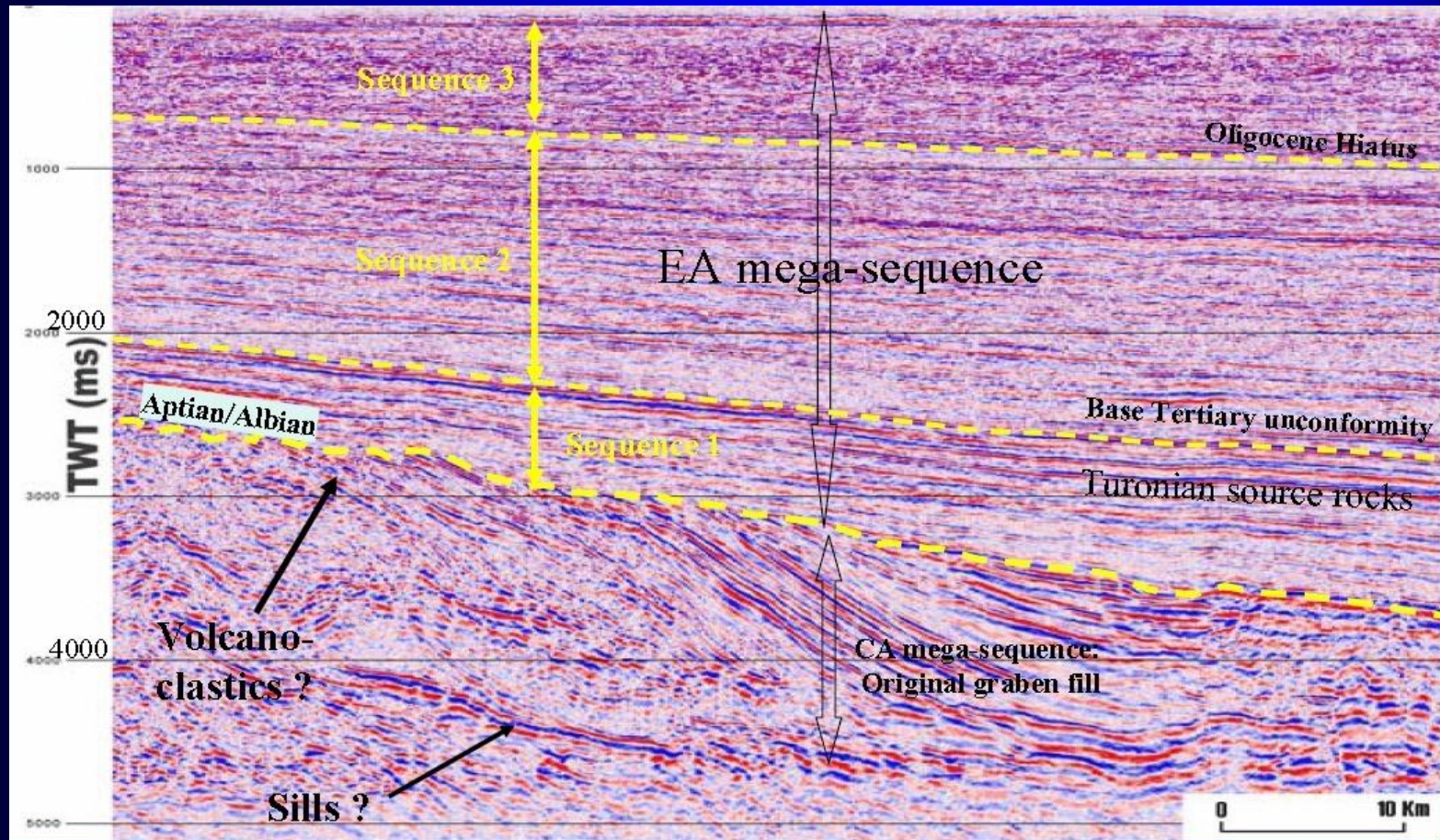


1 MILE



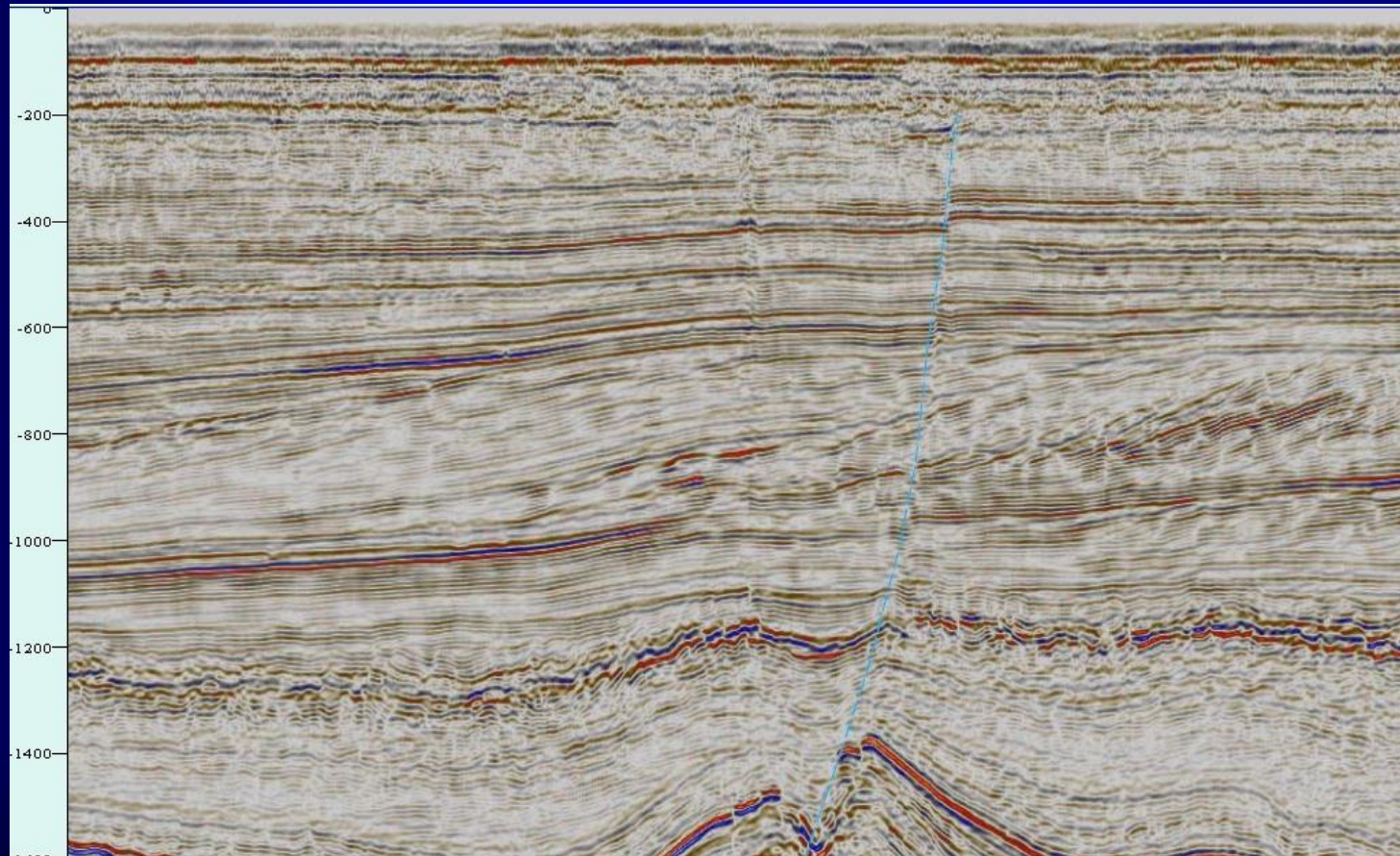
Seismic Sequence Stratigraphy

Sequences & Mega sequence



Seismic Sequence Stratigraphy

Outbuilding delta



ALI BAKR

Seismic Sequence Stratigraphy

Principle 6

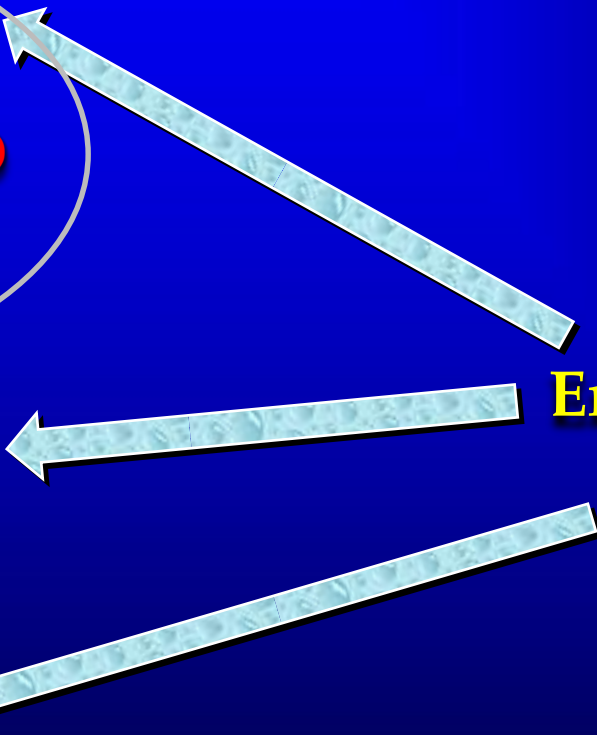
Non marine environments

- Alluvial environments (fans)
- Fluvial environments
- Lacustrine environments
- Aeolian environments

Coastal (marginal marine)
environments

Marine environments

Environments

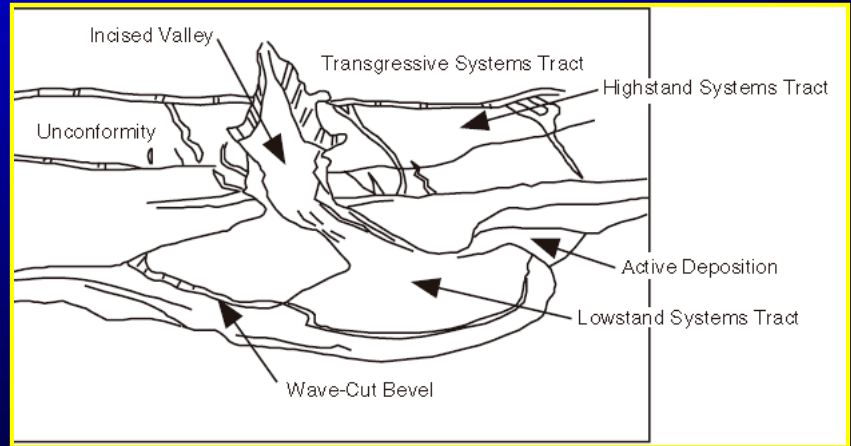


Seismic Sequence Stratigraphy

Principle 6

Alluvial & Lacustrine Facies Alluvial Facies

- Typically sand and gravel rich: proximal portion of drainage network
- Framework facies are oriented parallel with depositional dip (Note: avalanches and debris flows on fans commonly follow stream courses, these are topographic lows), but complex internal relationships such as down cutting and lateral incision result in highly complex reservoir distribution
- Internal distribution of permeability within the reservoir body is highly varied, both laterally and vertically, thus reservoir units are internally highly Heterogeneous



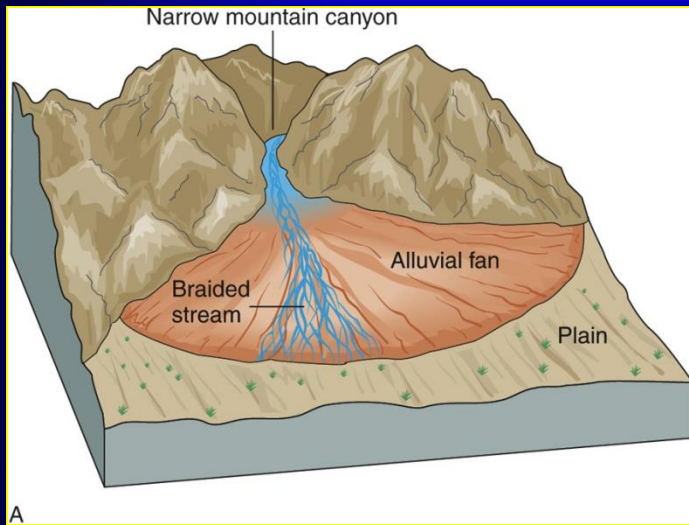
Seismic Sequence Stratigraphy

Principle 6

Alluvial & Lacustrine Facies

Alluvial Facies

Alluvial fan is a fan-shaped deposit of alluvium found where a stream flows out of a mountain onto flatter terrain.



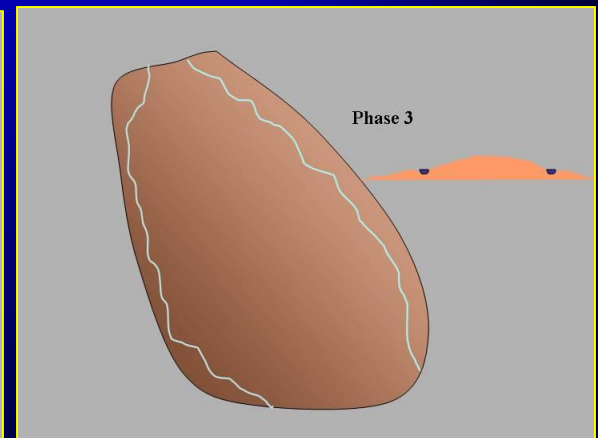
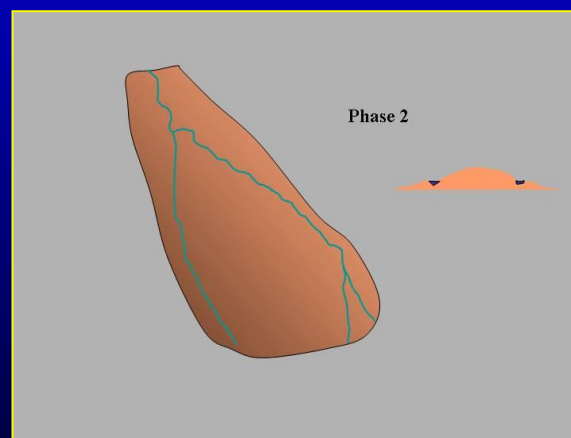
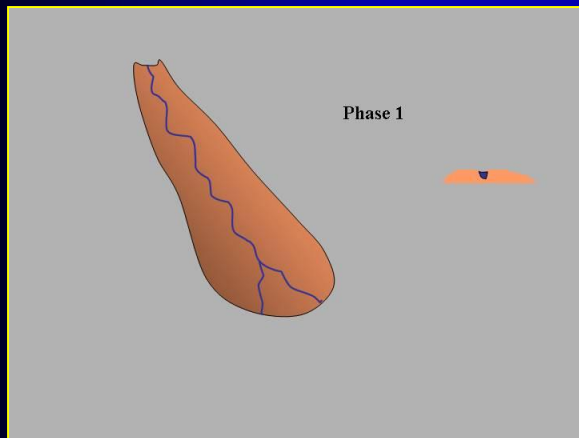
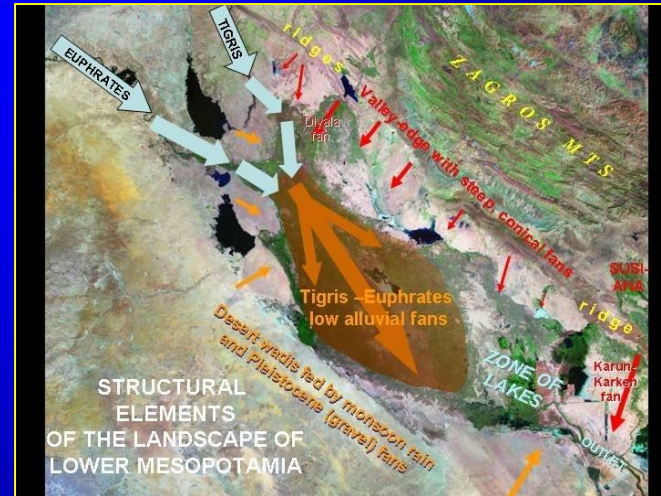
An alluvial fan in Death Valley

Seismic Sequence Stratigraphy

Principle 6

Alluvial & Lacustrine Facies Alluvial Facies

Growth of Alluvial fan



Seismic Sequence Stratigraphy

Principle 6

Alluvial & Lacustrine Facies Alluvial Facies

- Lack of fine grained sealing and source facies is a major problem. The nature of adjacent systems is important for hydrocarbon sourcing
- Most reservoirs are structural traps. Continuity of sands (continuity of lateral and vertical permeability) and absence of seals makes tectonic structure a requirement for most traps.
- Localization of alluvial fans near basin margin faults also makes tectonic structure important.



Seismic Sequence Stratigraphy

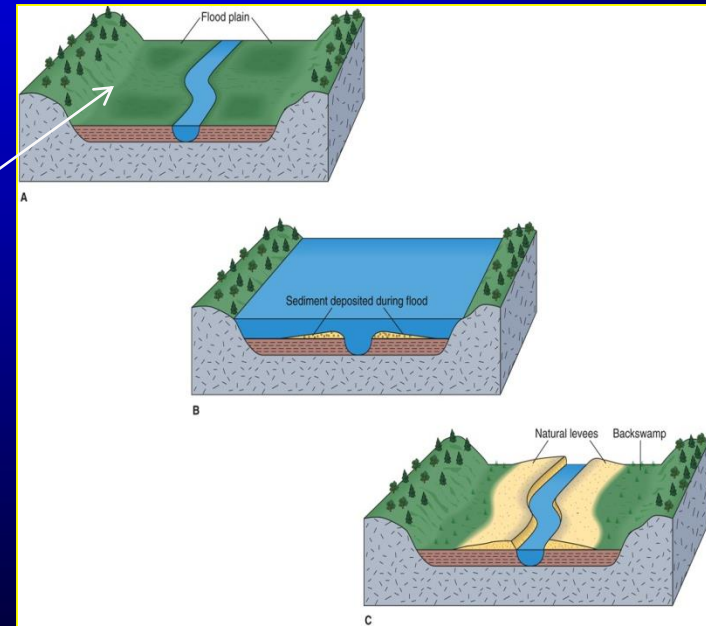
Principle 6

Alluvial & Lacustrine Facies

Alluvial Facies-Flood Plain

Flood Plain

- is a broad strip of land built up by sedimentation on either side of a stream channel.
- During floods, flood plains may be covered with water carrying suspended silt and clay.
- When the flood water recedes, these fine-grained sediments are left behind as a horizontal deposit.

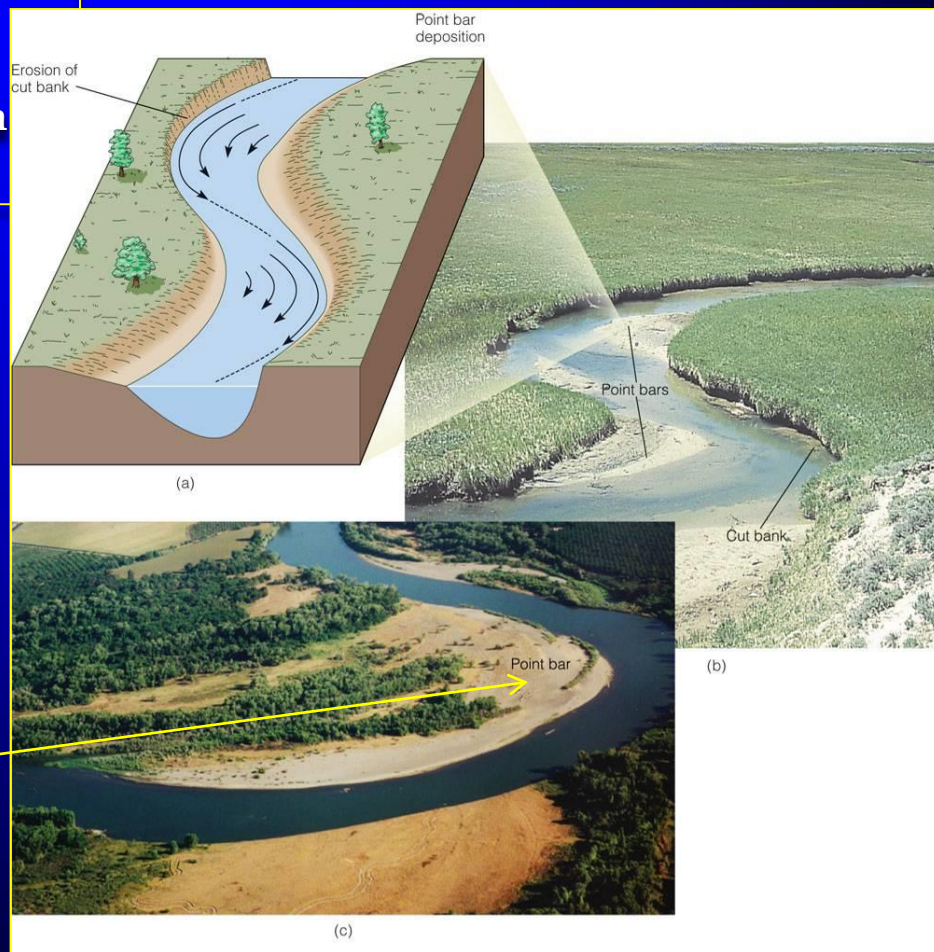
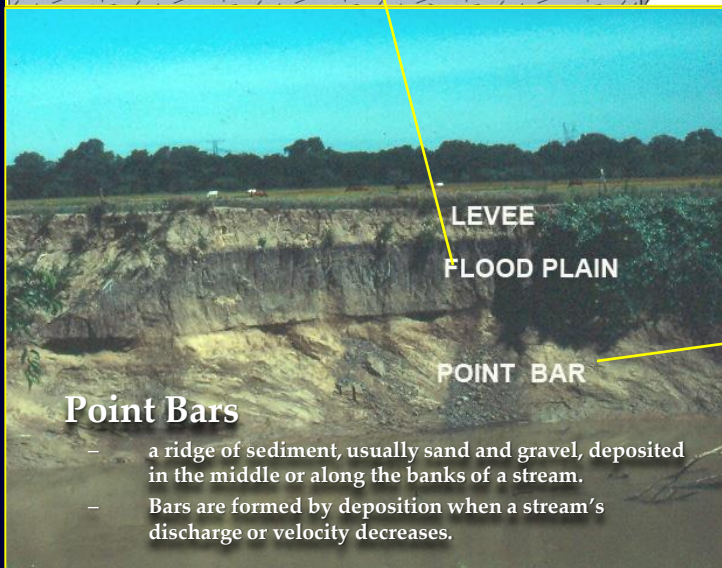
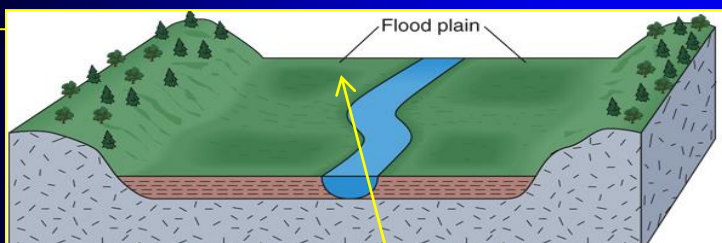


Seismic Sequence Stratigraphy

Principle 6

Alluvial & Lacustrine Facies

Alluvial Facies-Point Bar & Flood Plain



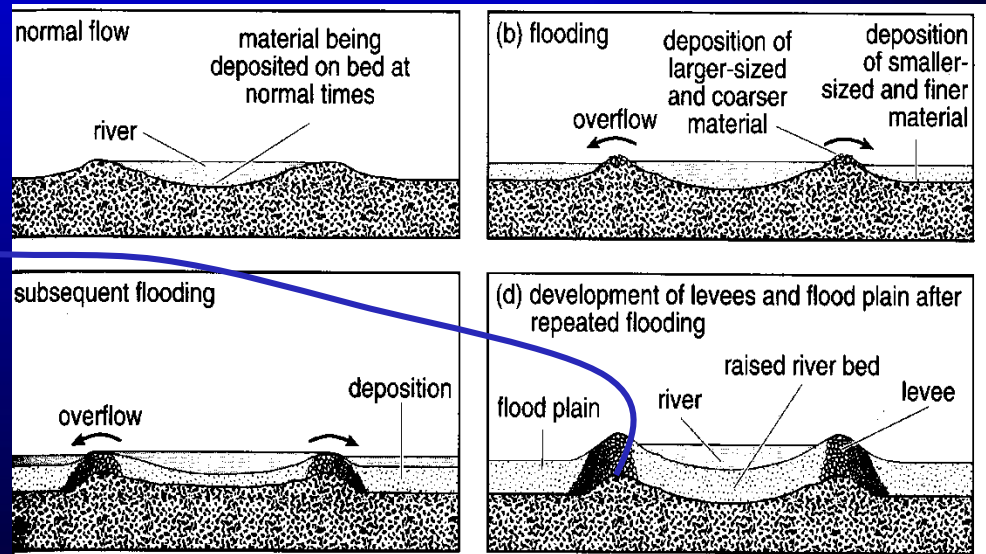
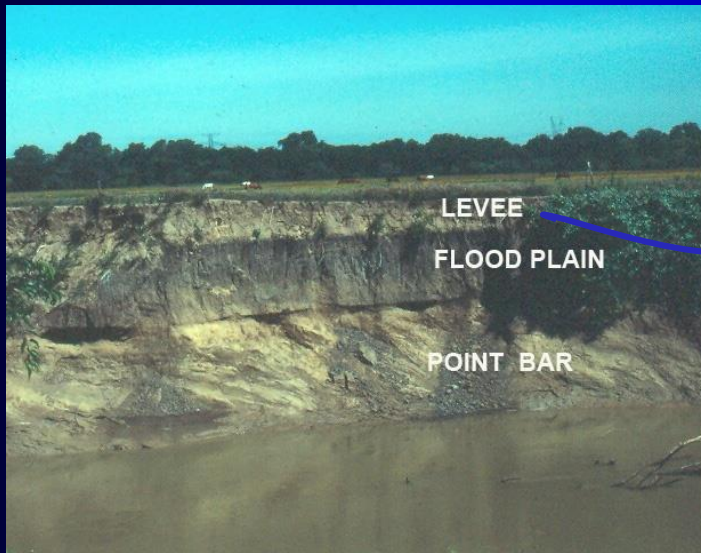
Seismic Sequence Stratigraphy

Principle 6

Alluvial & Lacustrine Facies

Alluvial Facies-Levee

- When a river overflows its bank, the larger and coarser materials will be deposited first.
- This forms a small, natural embankment alongside the channel.
- This embankment is called a levee



Seismic Sequence Stratigraphy

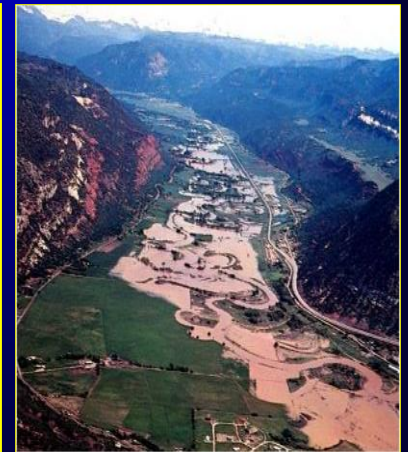
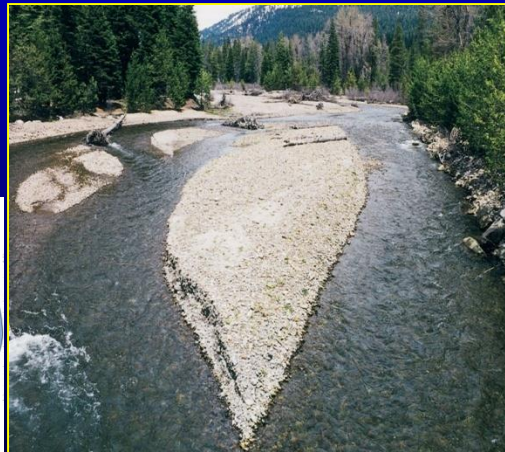
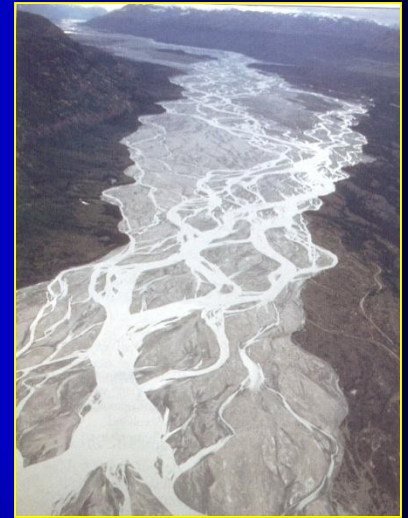
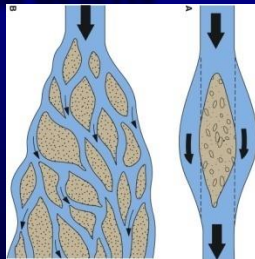
Principle 6

Alluvial & Lacustrine Facies

Alluvial Facies-Braided Stream

Braided Stream

- Stream is flowing in a network of interconnected rivulets around numerous bars.
- Characteristically has a wide, shallow channel.
- A stream tends to become braided when it is heavily loaded with sediment and has banks that are easily eroded.
- This pattern can develop in deserts



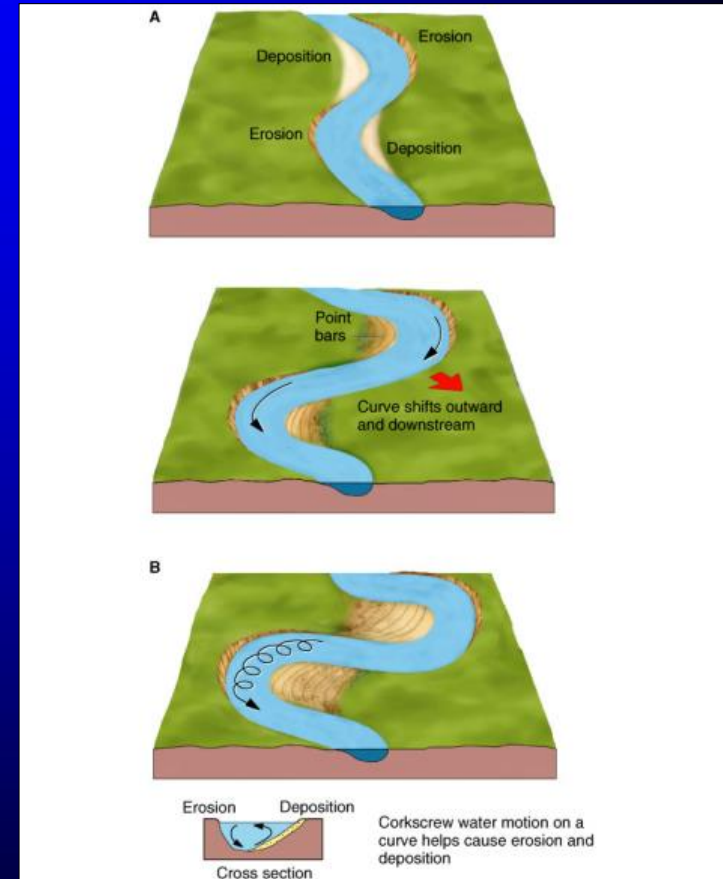
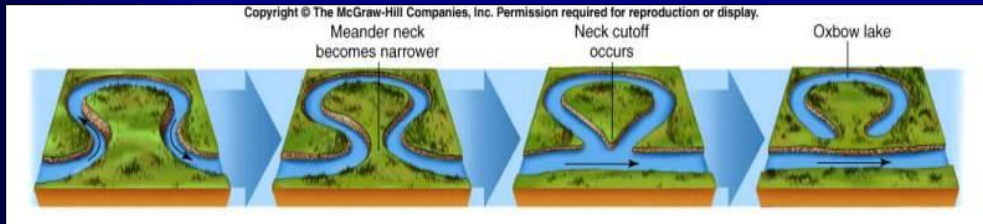
Seismic Sequence Stratigraphy

Principle 6

Alluvial & Lacustrine Facies

Alluvial Facies-Meandering Streams

- Meandering streams are the result of differences in water velocity found on the outside and on the inside of a curve.
 - Higher velocity on the outside promotes erosion
 - Lower velocity on the inside promotes deposition.
 - Point Bars are created on the inside of curves.
 - Continued erosion and deposition cause them to migrate back and forth across a flat valley floor.
- A river may form a meander cutoff, a new, shorter channel across the narrow neck of a meander.
 - The cutoff meander becomes a crescent-shaped oxbow lake.

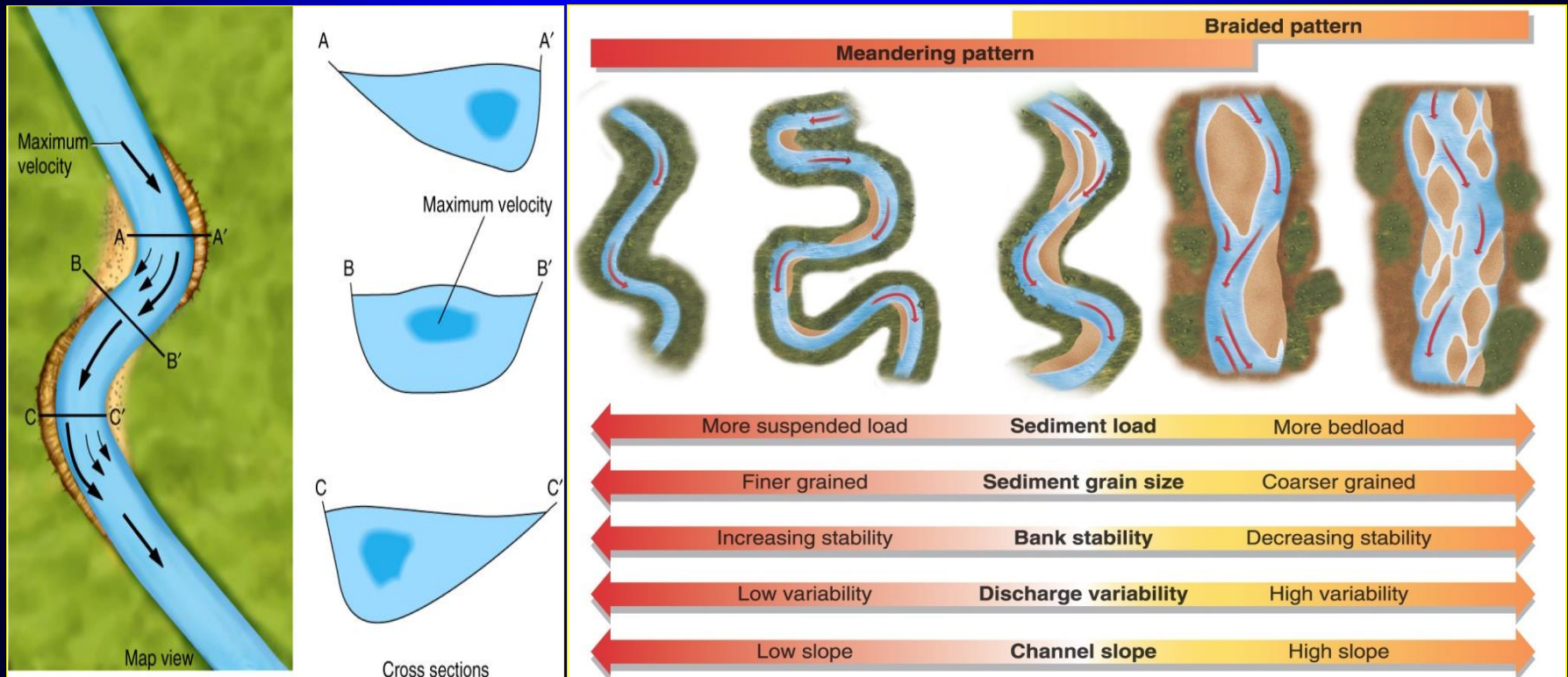


Seismic Sequence Stratigraphy

Principle 6

Alluvial & Lacustrine Facies

Alluvial Facies-Braided Stream versus Meandering



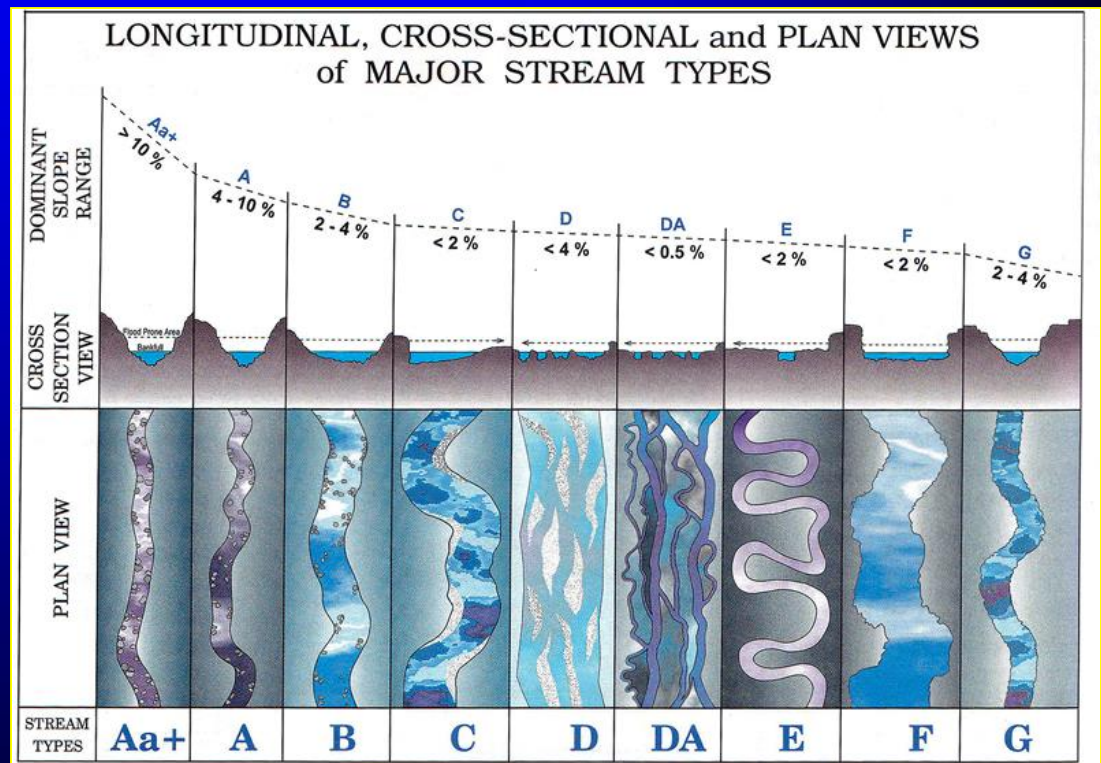
Seismic Sequence Stratigraphy

Principle 6

Alluvial & Lacustrine Facies

Alluvial Facies-Meandering Streams

- “C” and “G” channel carry water and sediment most efficiently.
- Straight channel Aa+, A and B have no flood plain.
 - Deposition occurs under low flow.
 - Erosion occurs under high flow.
- “E” channel has too tight curves.



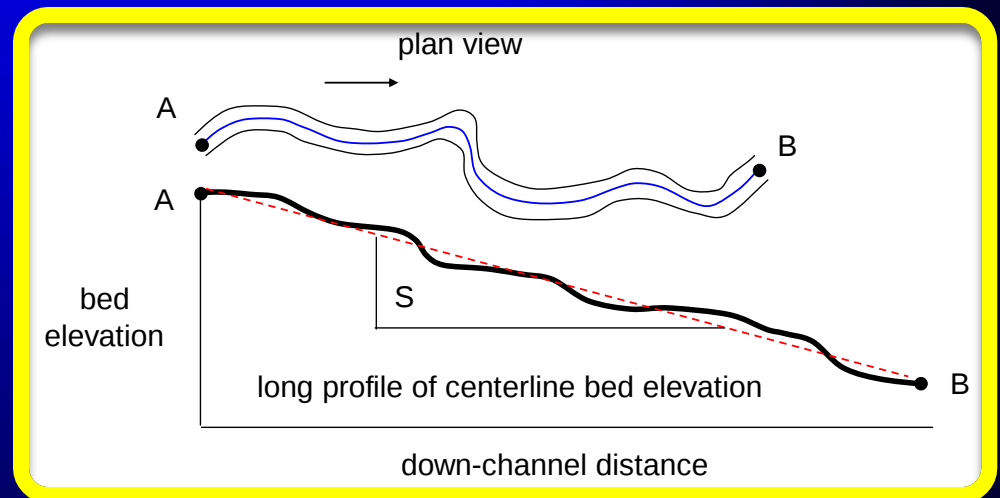
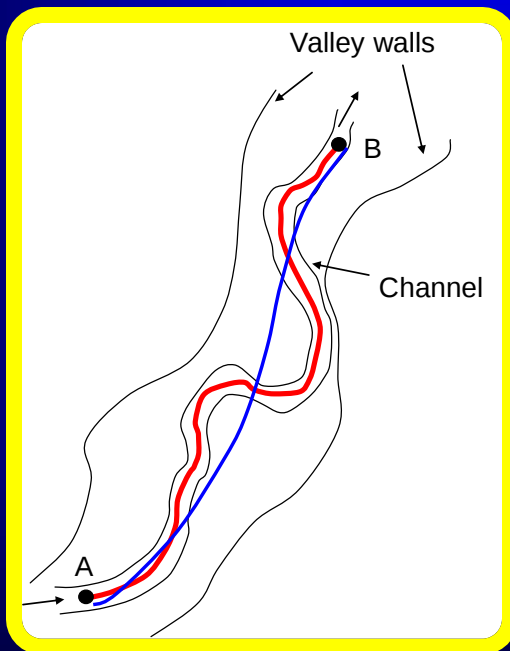
Seismic Sequence Stratigraphy

Principle 6

Alluvial & Lacustrine Facies

Alluvial Facies-Meandering Streams

Channel slop is different than down valley bed slop



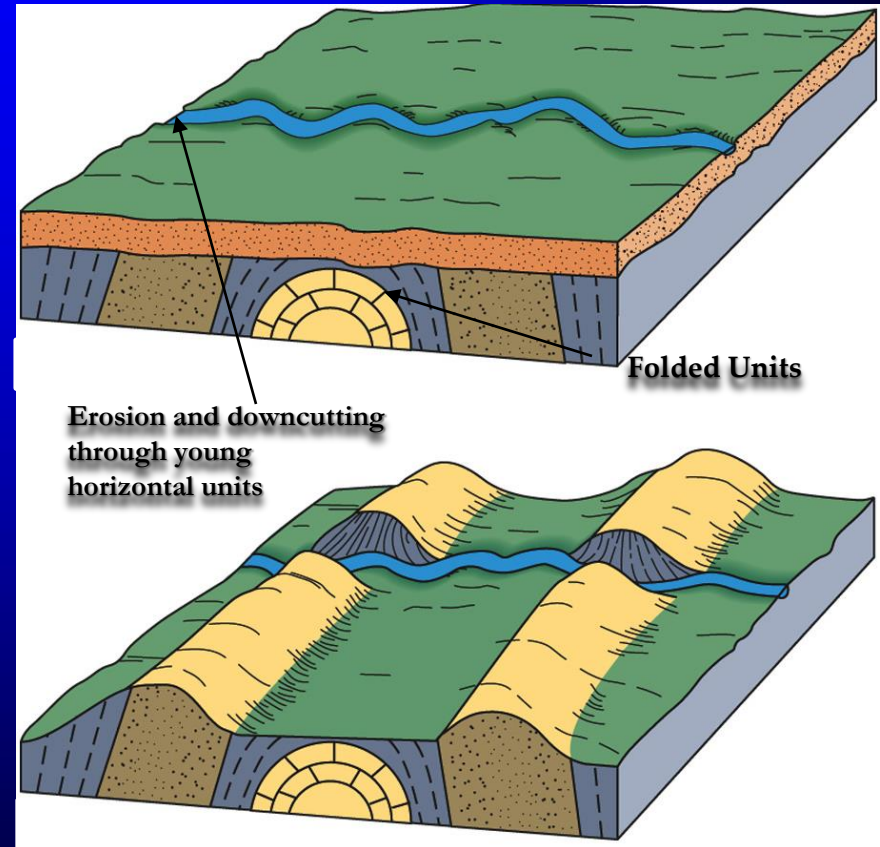
Seismic Sequence Stratigraphy

Principle 6

Alluvial & Lacustrine Facies

Alluvial Facies-Meandering Streams

- Channels may or may not follow the old structure configuration



Seismic Sequence Stratigraphy

Principle 6

Alluvial & Lacustrine Facies Alluvial Facies

- Lack of fine grained sealing and source facies is a major problem. The nature of adjacent systems is important for hydrocarbon sourcing
- Most reservoirs are structural traps. Continuity of sands (continuity of lateral and vertical permeability) and absence of seals makes tectonic structure a requirement for most traps.
- Localization of alluvial fans near basin margin faults also makes tectonic structure important.



Seismic Sequence Stratigraphy

Principle 6

Alluvial & Lacustrine Facies Lacustrine Facies

Three Main Facies Associations



Overfilled



Fluvial-
Lacustrine



Balanced filled



Fluctuating
Profundal



Underfilled



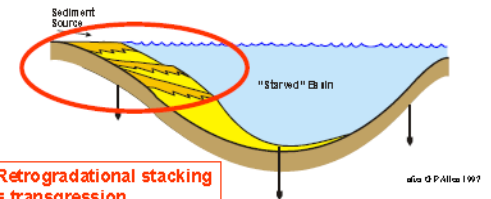
Evaporitic

Lacustrine Deposits

Lakes form where rate of accommodation (subsidence) outstrips rate of sediment supply, and sufficient precipitation is available to at least temporarily fill a depression with water.

Subsidence > Sediment supply
AND
Precipitation >= Evaporation (at least some of the time)
=
Lake

Accommodation Space

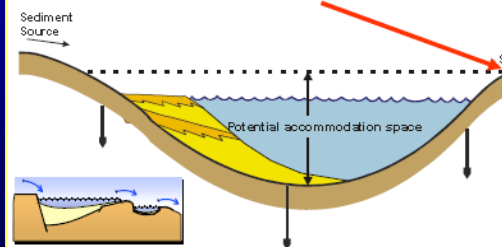


Retrogradational stacking = transgression

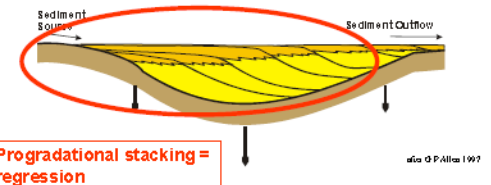
Accom. Space >> Sediment Supply

Accommodation Space

In Lakes: Position of sill (lake spill point) important



Accommodation Space



Progradational stacking = regression

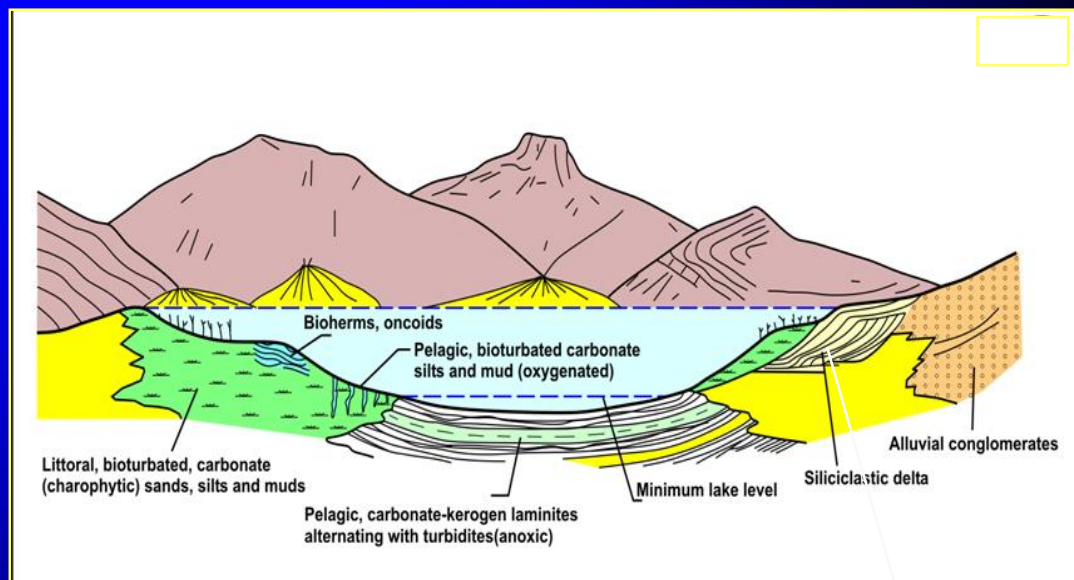
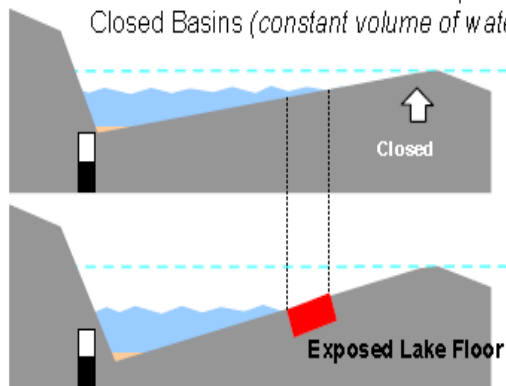
Accom. Space << Sediment Supply

Seismic Sequence Stratigraphy

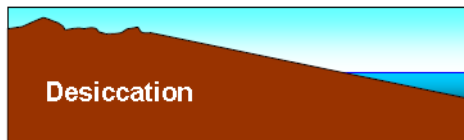
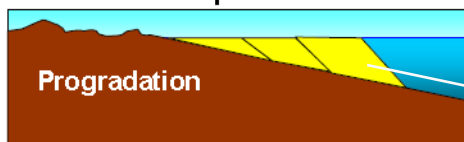
Principle 6 Alluvial & Lacustrine Facies Lacustrine Facies

Response to Subsidence

- Subsidence causes Lake Floor Exposure in Closed Basins (*constant volume of water*)



Two Modes of Shoreline Movement are Important



Overfilled Lake

- Prograding Deltas
- Stable Lake Level
- Well Connected Reservoirs



Seismic Sequence Stratigraphy

Principle 6

Alluvial & Lacustrine Facies

Lacustrine Facies

- Lacustrine sediments respond to lake-level changes, where lake level fall leads to a downward shift of facies tracts, whereas lake-level rise causes a landward jump of deltaic and marginal lakes facies.
- Two types of lakes systems can be distinguished:
- 1) Lakes (e.g. open and closed lakes) far away from the sea and located above sea-level. Their rising and falling are controlled by local factors.

Seismic Sequence Stratigraphy

Principle 6

Alluvial & Lacustrine Facies

Lacustrine Facies

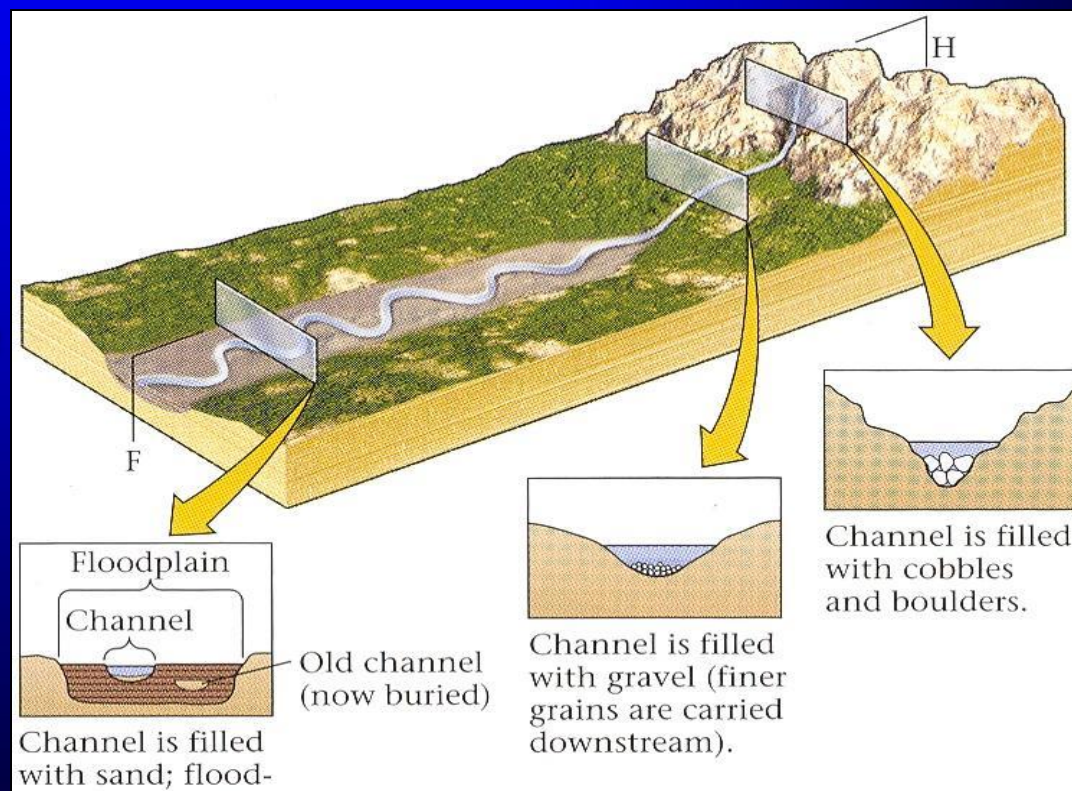
2) Large lakes in lowlands with limited terrigenous sediment supply, may be occasionally be influenced by sea-level changes.

- Depending on the climate, lakes vary from open to closed and lake-level fluctuations have low-amplitude.
- They develop thin sequences ranging from 3rd order sequences of the marine realm to high-frequency cyclic phenomena.

Seismic Sequence Stratigraphy

Principle 6 Alluvial & Lacustrine Facies

The character of river
sediment varies with
distance from the source



Seismic Sequence Stratigraphy

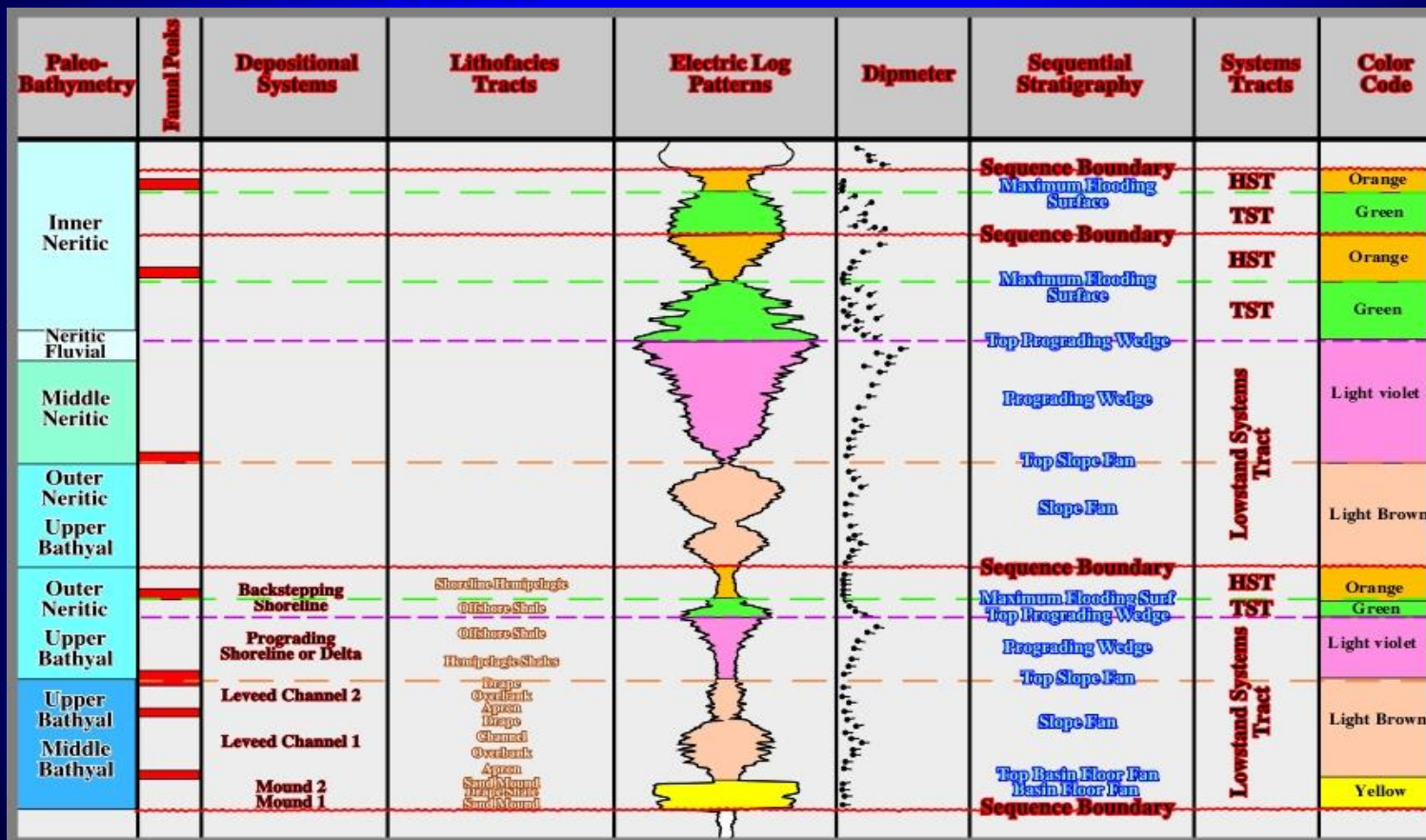
Principle 6 Alluvial & Lacustrine Facies

	ALLUVIAL FAN	FLUVIAL	LACUSTRINE
Rock Type	Breccia, conglomerate, arkose	Conglomerate, sandstone, siltstone, shale	Siltstone, shale, limestone, or evaporites (gypsum)
Composition	Terrigenous	Terrigenous	Terrigenous, carbonate, or evaporite
Color	Brown or red	Brown or red	Black, brown, gray, green
Grain Size	Clay to gravel	Clay to gravel (Fining upward)	Clay to silt or sand (Coarsening upward)
Grain Shape	Angular	Rounded to angular	---
Sorting	Poor	Variable	Variable
Inorganic Sedimentary Structures	Cross-bedding and graded bedding	Asymmetrical ripples, cross-bedding, graded bedding, tool marks	Symmetrical ripples, lamination, cross-bedding, graded bedding, mudcracks, raindrop prints

Seismic Sequence Stratigraphy

Principle 6

Alluvial & Lacustrine Facies



Seismic Sequence Stratigraphy

• CYLINDRICAL

- Eolian, Carbonate shelves, braided fluvial, ...
- Clean

• FUNNEL

- Crevasse splay, barrier island, shallow marine planar beds, distributary mouth bar
- Coarsening upward

• BELL

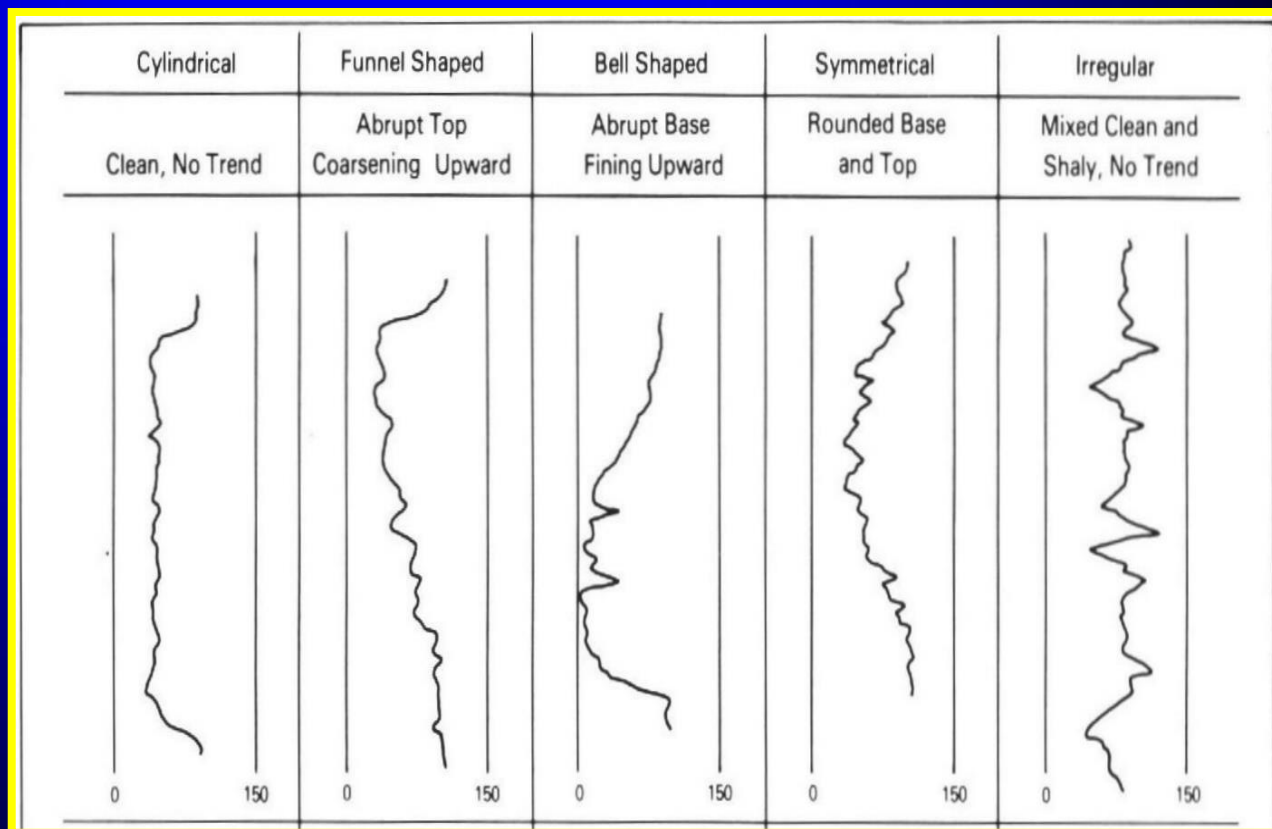
- Sharp basal contact
- Point bar
- Channel

• SYMMETRICAL

- Rounded base & top
- Offshore bars

• IRREGULAR

- Shaly, no trends visible
- Floodplain, carbonate slopes



Seismic Sequence Stratigraphy

Table 1 *Log types, properties measured, and geological uses.*

Log	Property Measured	Units	Geological Uses
Spontaneous potential	Natural electric potential (compared to drilling mud)	Millivolts	Lithology (in some cases), correlation, curve shape analysis, identification of porous zones.
Resistivity	Resistance to electric current flow	Ohm-metres	Identification of coals, bentonites, fluid evaluation.
Gamma-ray	Natural radioactivity — related to K, Th, U	API units	Lithology (shaliness), correlation, curve shape analysis.
Sonic	Velocity of compressional sound wave	Microseconds/metre	Identification of porous zones, coal, tightly cemented zones.
Caliper	Size of hole	Centimetres	Evaluate hole conditions and reliability of other logs.
Neutron	Concentrations of hydrogen (water and hydrocarbons) in pores	Per cent porosity	Identification of porous zones, cross plots with sonic, density logs for empirical separation of lithologies.
Density	Bulk density (electron density) includes pore fluid in measurement	Kilograms per cubic metre (gm/cm ³)	Identification of some lithologies such as anhydrite, halite, nonporous carbonates.
Dipmeter	Orientation of dipping surfaces by resistivity changes	Degrees (and direction)	Structural analysis, stratigraphic analysis

Seismic Sequence Stratigraphy

- No pattern is unique
- The scale of succession is very important in seismic interpretation: do not over-detail the geologic information, since seismic data will generally average small intervals into medium ones.
- Well logs allow for recognition of discontinuities and unconformities, setting a firm base for Seismic Stratigraphy.

7- 4D

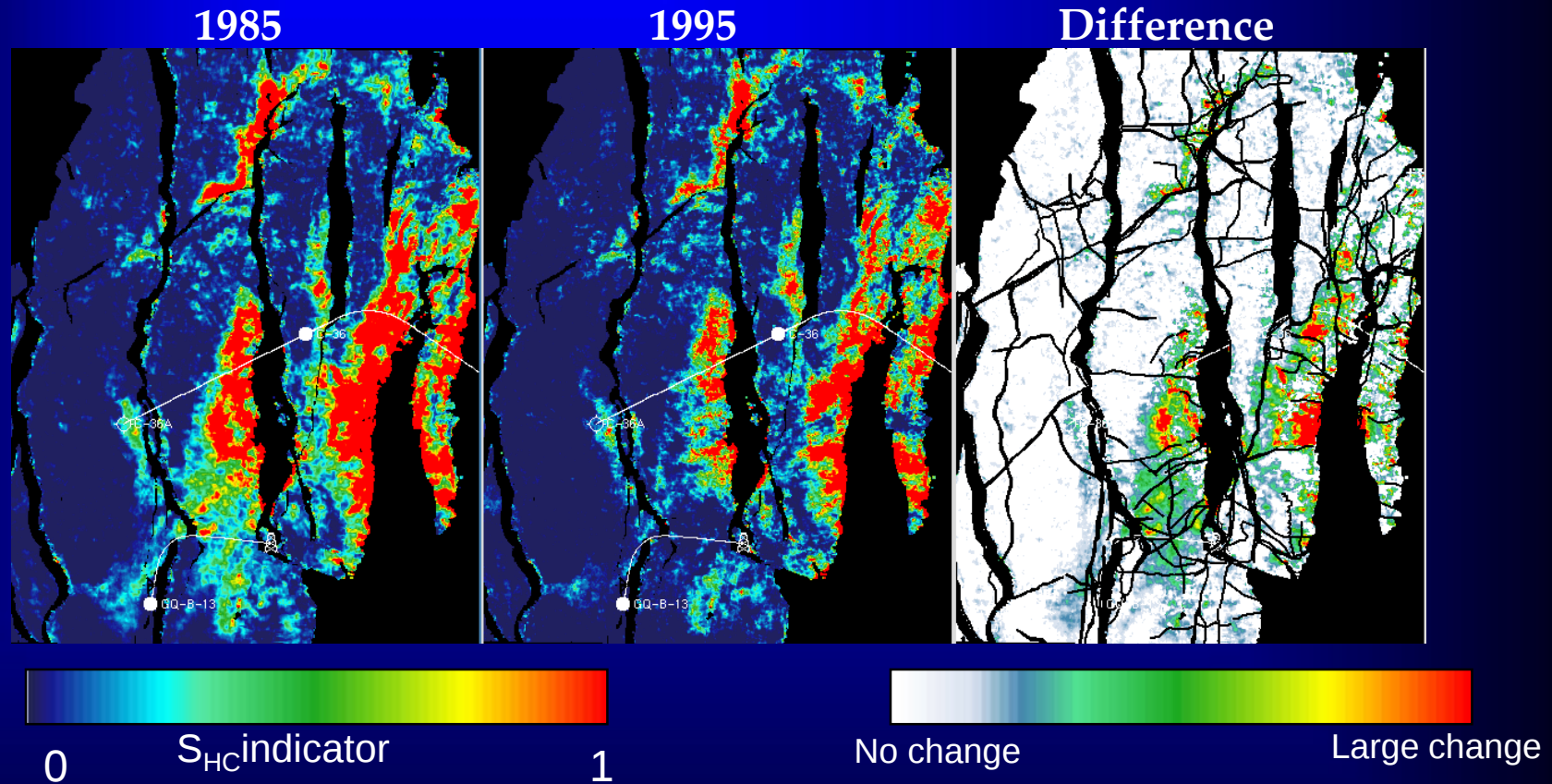
What is 4D Seismic?

- Is the analysis of differences found in seismic surveys repeated in an area where substantial changes in the subsurface have occurred, due to production processes
 - Qualitative
 - Quantitative
- Provides information with lateral continuity that provides a VISION of actual changes in the reservoir
 - Fluid substitution
 - Temperature
 - ...

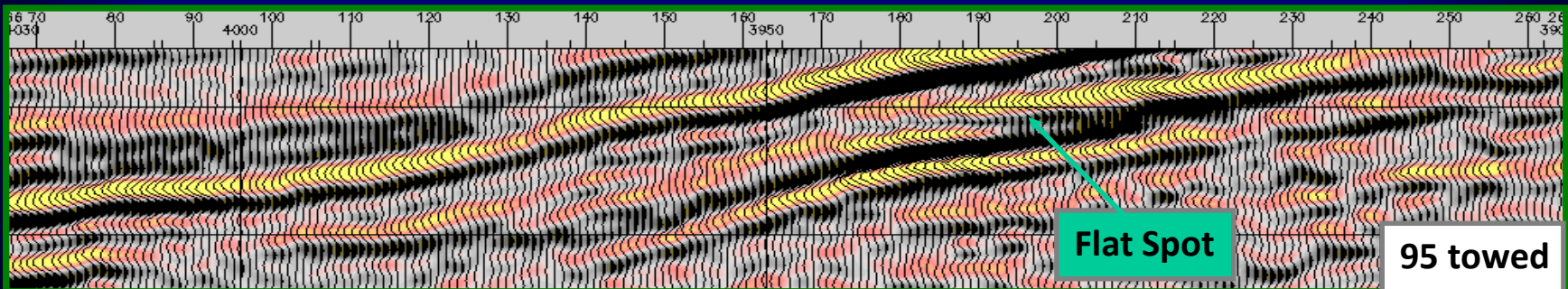
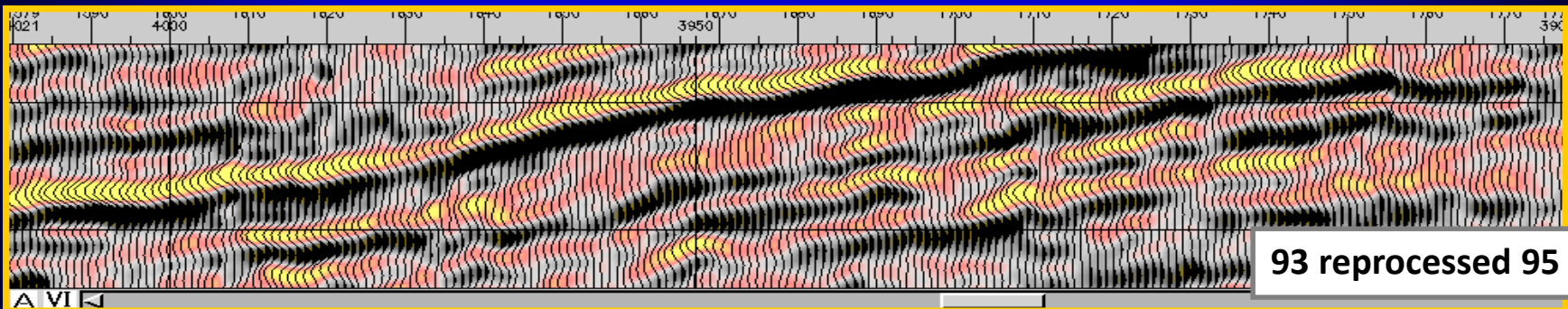
4D Seismic - the Concept

- Also known as Seismic Reservoir Monitoring or Time-Lapse Seismic
- Consists of 3D seismic surveys, repeated after intervals of substantial production
- Successive surveys analysed for differences
- Observes fluid changes in the reservoir
- Available between & beyond the wells

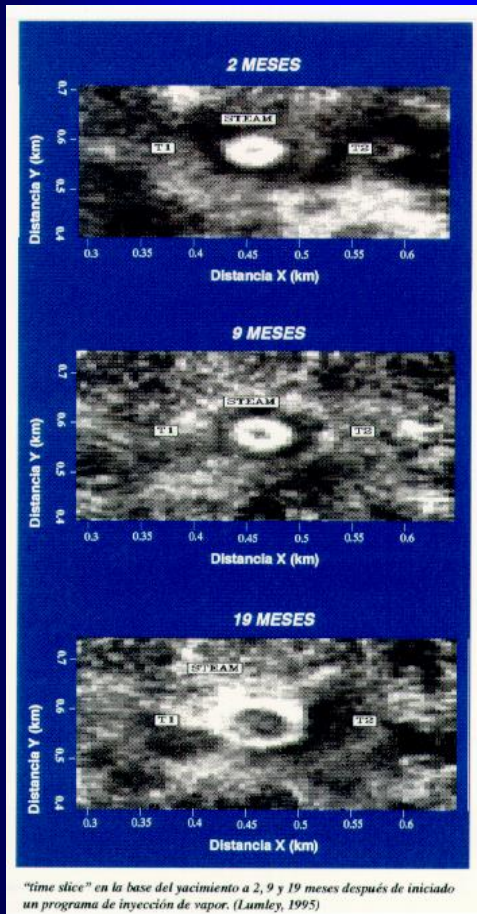
Classification of Gullfaks data



34 well locations selected; additional 600 million bbl producible reserves found as result of 4D



Pioneer Examples: Duri Field



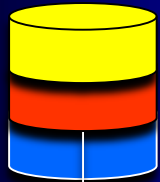
- Seismic image of DURI field, where effects of steam injection are easily visualized in the seismic data
- D. Lumley, 1995

4D Interpretation Workflows

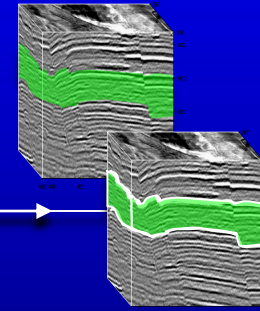
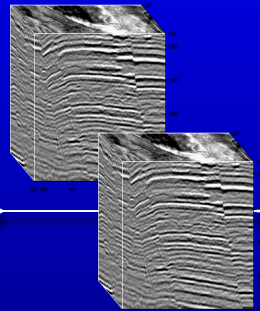
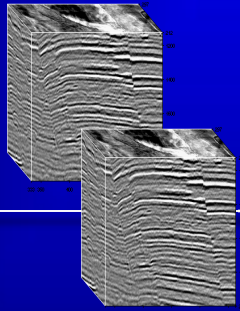
- Fluid substitution modelling
- Seismic repeatability assessment
- Seismic interpretation
- Seismic attribute extraction
- Classification (Inversion)
- Reservoir optimisation

4D Workflow

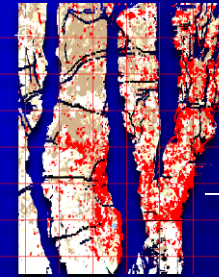
Fluid
substitution,
AVO modelling



Interpretation



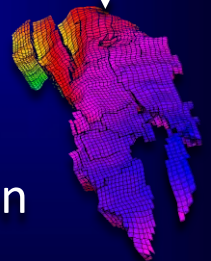
Inversion-
Classification



Seismic repeatability
assessment, wavelet,
etc..

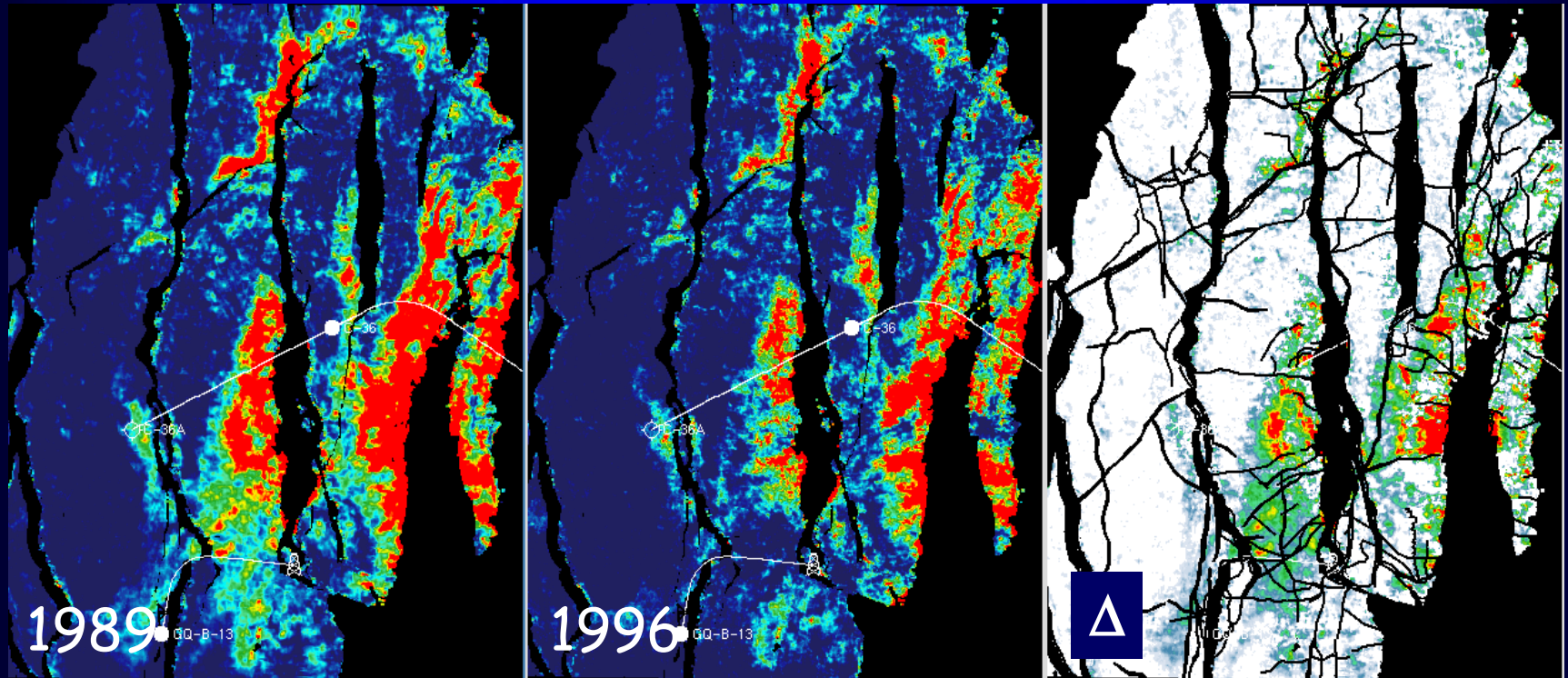
Seismic attribute
extraction

Reservoir
optimisation



4D (Time-Lapse) Seismic Gullfaks Field, North Sea

Mapping fluid movements and identifying unswept hydrocarbons



0 S_{HC} indicator 1



No change Large change

4D Summary

- 4D seismic provide important information for decision making analysis in reservoir management
- Tailor made interpretation tools and workflows for 4D analysis
- Demonstrated the use of qualitative or semi-quantitative 4D analysis for updating reservoir models
- Seismic to Simulation and Simulation to Seismic (S2S) are established workflows
- Beyond qualitative interpretation, the link between reservoir engineering and geophysics via rock physics enables quantitative 4D analysis for reservoir management

Scale

Uncertainty

Resolution

Environment

Rock (core)

Low size high
accuracy

Well (Logs)

Mid Size Mid
Accuracy

Field (Seismic)

Large Size Low
Accuracy

AVO

AVO Attributes

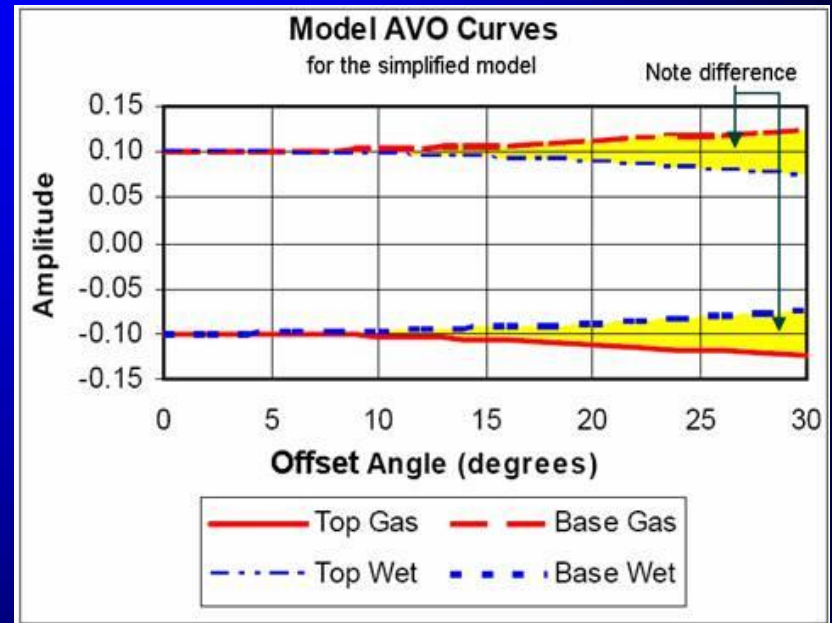
Using the values for V_P , V_S , and density ρ , we can now work out the values for the AVO intercept and gradient for the wet and gas sands. For the wet sand, the V_P/V_S ratio in both the sand and shale layer is equal to 2. As shown in this leads to the simplification that $B = -A$ for both the top and base of the layer.

Using the parameters shown in the figure gives: $ATOP_WET = BBASE_WET = +0.1$ and $ABASE_WET = BTOP_WET = -0.1$.

For the gas sand, the V_P/V_S ratio is equal to 1.65, and the intercept does not simplify as it did the wet sand.

However, the calculation is still straightforward, and leads to $ATOP_GAS = BTOP_GAS = -0.1$ and $ABASE_GAS = BBASE_GAS = +0.1$. Note that, for the gas case, $A=B$ for both the top and base of the layer.

The AVO curves for the wet and gas cases are shown in figure 4, for an angular aperture of 0° to 30° . It is observed that the absolute values of the gas sand curves show an increase in amplitude, whereas the absolute values of the wet sand curves show a decrease in amplitude. These values do fall within a reasonable petrophysical range for class 3 anomalies.



AVO

AVO Attributes

After scaling each of the values of A and B by a factor of 10 (to give values of +1 and -1) they have been put on an A-B cross plot, as shown in Figure 5. In our example, the wet points (shown as solid blue circles) establish the wet sand-shale trend, and the top and base gas (shown as solid red circles) plot in the other two quadrants of the A-B crossplot. This is a typical class 3 AVO anomaly (Rutherford and Williams, 1989), caused by gas saturation reducing the sand impedance and the V_p/V_s ratio of the sand encased in the shale.

